US Army Corps
of Engineers
Construction Engineering
Research Laboratory

USACERL TECHNICAL REPORT E-91/05
August 1991
Coal Use Technologies

AD-A240 021

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The Economics and Application of Coal Water Fuel in Army Heat Plants

by
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Congress has directed that Department of Defense steam generating plants in the United States be converted to coal-burning facilities to reduce the dependence on petroleum fuels. To help meet this requirement, the U.S. Army Construction Engineering Research Laboratory assessed coal water fuel (CWF) which has the potential to be an efficient, inexpensive, and reliable replacement for petroleum fuels. However, the actual costs of producing and burning CWF are not yet known. Researchers (1) developed a cost model for CWF, (2) assessed the engineering and economic requirements of converting a boiler to burn CWF, and (3) designed a complete firing system based on a specification for CWF developed to ensure that the fuel will work in a converted boiler.

This study indicated that a CWF retrofit is technically feasible and will soon become economically attractive. CWF can cost as little as $2.61 per million British thermal units (MBtu) and an industrial sized oil-designed boiler can be retrofitted to burn CWF for approximately $1.9 million. CWF should be demonstrated in a long-term test program to determine equipment specifications, operational characteristics, systems control requirements, and maintenance needs.

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY (Leave Blank)	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	August 1991	Final

4. TITLE AND SUBTITLE

The Economics and Application of Coal Water Fuel in Army Heat Plants

5. FUNDING NUMBERS

PE 4A162781
PR AT45
TA D
WU 006

6. AUTHOR(S)

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7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

U.S. Army Construction Engineering Research Laboratory (USACERL)
PO Box 9005
Champaign, IL 61826-9005

8. PERFORMING ORGANIZATION REPORT NUMBER

TR E-91/05

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

COMMANDER
US Army Engineering and Housing Support Center
ATTN: CEHSC-FU
Fort Belvoir, VA 22060-5580

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES

Copies are available from the National Technical Information Service, 5285 Port Royal Road, Springfield, VA 22161

12a. DISTRIBUTION/AVAILABILITY STATEMENT

Approved for public release; distribution is unlimited.

12b. DISTRIBUTION CODE

13. ABSTRACT (Maximum 200 words)

Congress has directed that Department of Defense steam generating plants in the United States be converted to coal-burning facilities to reduce the dependence on petroleum fuels. To help meet this requirement, the U.S. Army Construction Engineering Research Laboratory assessed coal water fuel (CWF) which has the potential to be an efficient, inexpensive, and reliable replacement for petroleum fuels. However, the actual costs of producing and burning CWF are not yet known. Researchers (1) developed a cost model for CWF, (2) assessed the engineering and economic requirements of converting a boiler to burn CWF, and (3) designed a complete firing system based on a specification for CWF developed to ensure that the fuel will work in a converted boiler.

This study indicated that a CWF retrofit is technically feasible and will soon become economically attractive. CWF can cost as little as $2.61 per million British thermal units (MBtu) and an industrial sized oil-designed boiler can be retrofitted to burn CWF for approximately $1.9 million. CWF should be demonstrated in a long-term test program to determine equipment specifications, operational characteristics, systems control requirements, and maintenance needs.

14. SUBJECT TERMS

coal water fuel

15. NUMBER OF PAGES

56

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	SAR

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std 239-18
298-102

FOREWORD

This study was conducted for the U.S. Army Engineering and Housing Support Center (USAEHSC) under Project 4A162781AT45, "Energy and Energy Conservation"; Technical Area D; Work Unit 006, "Coal Use Technologies." The USAEHSC Technical Monitor was Mr. B. Wasserman.

This research was performed by the Energy Systems Division (ES) of the U.S. Army Construction Engineering Research Laboratory (USACERL). Dr. Gilbert R. Williamson is Chief of USACERL-ES. Mr. Gary W. Schanche is Team Leader of USACERL's Fuel and Power System Team. The technical editor was Gloria J. Wienke, USACERL Information Management Office.

COL Everett R. Thomas is Commander and Director of USACERL, and Dr. L.R. Shaffer is Technical Director.

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1 INTRODUCTION

Background

The Defense Appropriations Act of Fiscal Year (FY) 1986 (PL 99-190), Section B110, directed that Department of Defense steam generating plants in the United States be converted to coal-burning facilities to reduce the dependence on petroleum fuels. To help meet this requirement, the U.S. Army Engineering and Housing Support Center (USAEHSC) asked the U.S. Army Construction Engineering Research Laboratory to assess the technical and economic feasibility of coal-based fuels that have the potential to replace petroleum fuels.

To burn a coal-based fuel successfully and economically, it is necessary that this fuel be easily handled, compatible with existing fuel handling equipment, and that it burn quickly in the small furnaces used for oil and gas. Coal typically needs more time to burn completely than oil or gas and most facilities that burn oil or gas do not have boilers large enough to allow for this extra burning time. Moreover, most heat plants typically do not have the space required for coal handling equipment.

On the other hand, coal water fuel (CWF) is easily handled, compatible with existing fuel handling equipment, and it can burn quickly in small furnaces. It is simply a mixture of ground coal, water, and small amounts of chemical additives that is handled and burned much like residual oil.

Many tests and demonstrations have been conducted using CWF. These programs have indicated that CWF will burn well in a modified oil boiler, with almost the same combustion efficiency as #6 oil. Although CWF has the potential to be an efficient, inexpensive, and reliable replacement for petroleum fuels, the actual costs of producing and burning CWF are not yet known.

Objectives

The objectives of this study were to (1) develop a cost model for CWF based on a production capacity compatible with the oil and natural gas requirements of a typical Army base, (2) assess the engineering and economic requirements for converting an oil-designed boiler to fire CWF, and (3) design a complete CWF firing system, including all control and auxiliary systems.

Approach

Before a design can be considered, a CWF specification must be developed to ensure that the fuel will work well in a boiler converted to burn it. Therefore, a description of CWF properties is given in Chapter 2 to provide a background for subsequent specifications and design.

The cost of a CWF retrofit is determined by designing a boiler system that can use CWF and, from this design, estimating the retrofit costs. The design and size of the modified boiler system are based on

the requirements of a typical Army heat plant. The design of a model CWF firing system is given in Chapter 3. The construction cost estimate derived from this design is also given.

A cost model for CWF production was achieved by designing a CWF production facility that is sufficiently generic that it could be implemented at a typical Army heat plant. The production cost was then determined from this design and the future cost of CWF was predicted from the cost model.

The primary concern in designing the facility was to make the capital cost and operating cost as low as possible because of the current marginal cost benefit of using CWF compared to oil and natural gas. The design was kept as simple as possible. However, a coal silo is specified to allow the facility to be smaller and to meet all local environmental regulations for coal storage. The CWF production facility design and the cost calculations in Chapter 4 give a high- and low-cost case scenario as well as a sensitivity analysis of coal and additive prices. The chapter also addresses economy of scale effects and provides an extended forecast price for CWF.

Mode of Technology Transfer

It is recommended that the information in this report be transferred as a Technical Note (TN).

2 CWF BACKGROUND

PL 99-190 directed that Department of Defense steam generating plants in the United States be converted to coal-burning facilities. This act also set a coal consumption target of 1,600,000 short tons* per year above the 1986 levels by FY 1994. Coal will provide a cheaper and more stable fuel in the future due to the availability and reliable supply afforded by the 64 x 10^9 metric tons of measured domestic coal reserves—27 percent of the world's supply.[1]

Although coal offers a lower price and a reliable supply, it does have some disadvantages. Coal is a solid fuel and is more difficult to handle and burn than oil and natural gas. Coal typically produces more sulfur dioxide (SO2) and particle emissions than oil and gas. Controlling these pollutants adds to both the capital and maintenance costs of a heat plant. The most immediate problem with using coal is in providing a means to burn it in existing oil-fired boilers.

Fortunately, coal-based fuels like CWF avoid most of the problems intrinsic to solid coal. CWF is a liquid and handles much like residual oil. The composition of CWF allows the coal to burn relatively fast, making it more compatible with oil- and gas-designed boilers. Furthermore, it is very easy to switch between CWF and oil or gas, allowing a dual fuel capability in an oil- or gas-designed boiler.

One consideration about CWF that makes it very attractive is that most physical and microbial techniques for cleaning coal to reduce its sulfur and ash content result in a slurry as a final product. Burning this slurry avoids the very expensive process of drying the coal. The advantage of using clean coal will become increasingly important in the future as air pollution regulations become stricter. In fact, cleaned coal could actually contain less sulphur than many #6 oils.[2]

CWF also lends itself to cofiring with a material that "absorbs" sulphur, such as limestone and dolomite. The "sorbent" can be blended with the slurry and will react with the sulphur during combustion. Thus, sulfur oxide (SOx) emissions can be reduced without modifying the boiler system.

Industry Experience

The feasibility of using CWF has been proven in the commercial sector. Development of coal water fuels began during the mid-1970's. Considerable activity and interest continued to build into the 1980's, resulting in a combined pilot plant with the capacity of approximately 40 to 50 tons/hr. Many American CWF manufacturers, burner manufacturers, research organizations, and government agencies have been involved with CWF testing. These include: Atlantic Research Corp, North American CWF Partnership (Ashland Oil and Babcock and Wilcox), Carbogel, CoaLiquid, Foster Wheeler, U.S. Fluidcarbon (subsidiary of Allis-Chalmers), OXCE (Occidental Petroleum and Combustion Engineering), Advanced Fuel Technology, Electrical Power Research Institute, Department of Energy, and Department of Defense. CWF tests have also been conducted in many foreign nations, including China, South Korea, Sweden, Japan, Canada, and Israel. Even though activity in the United States has slowed down in the past 3 years due to the low cost of oil, China, South Korea, and Japan are still actively developing their CWF programs.

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* Metric conversion factors are on page 33.

[1] N. Berkowitz, *An Introduction to Coal Technology* (Academic press, 1979), p 18.

[2] G. R. Northrup, *Survey of Microcleaning Methods for Application to Army Coal-Fired Plants*, Technical Report E-89/05/ADA206949 (U.S. Army Construction Engineering Research Laboratory [USACERL], December 1988).

The Electrical Power Research Institute (EPRI) sponsored a 35-day demonstration burn at DuPont's Memphis, TN plant in which 2400 tons of CWF were burned. The New Brunswick Electric Power Commission and Cape Breton Development Corporation have constructed a 4-ton/hr pilot plant to produce CWF to fire two small utility boilers at Chatham, New Brunswick, Canada. Nycol of Sweden has compiled 2580 hours of burn time, consuming 950,000 gallons of CWF at a boiler in Sundbyberg, Sweden. Most recently, CWF tests have been run at 40-MBtu/hr and 120-MBtu/hr boilers at the Beijing First Paper Mill, China. These tests have accumulated 1200 hours of burn time and consumed 920,000 gallons of CWF. In 1987, a 6-ton/hr CWF production facility was built in South Korea to support a test burn in a converted 150-MBtu/hr boiler. These demonstrations prove that CWF can be fired reliably without support fuel, that fuel switching can be performed routinely, and that a burner turndown of 4 to 1 is achievable.

The most recent study by the Department of Defense* on slurry fuels has been an Air Force test of a coal-oil mixture (50 percent coal, 40 percent oil, and 10 percent water) in March 1988. This test was conducted on a 50-MBtu/hr high temperature generator at Dover Air Force Base, Delaware, and compiled 300 hours of burn time, consuming 66,000 gallons of coal-oil mixture (COM).

Many other laboratory and pilot test burns have been conducted to study CWF's combustion and environmental emissions. These studies show that CWF can be burned with a combustion efficiency nearly equal to conventional pulverized coal firing (95 to 99 percent) and even without two-stage combustion, nitrogen oxide (NOx) levels of 150 to 250 parts per million (ppm) can be expected, which is 100 ppm lower than pulverized coal firing.

CWF Characteristics

The first step in developing a CWF retrofit design and a production facility is to specify a CWF composition that will economically achieve good combustion efficiency. Generally, increased combustion efficiency is associated with higher production costs. To understand the tradeoff between good combustion and good economics, an understanding of the combustion and flow properties (rheology) of CWF is required.

CWF handles very much like residual oil. It is more viscous at lower temperatures than #6 oil and can actually freeze. However, the viscosity lowers rapidly when heated. The coal particles in CWF make it very abrasive. CWF pumps must be able to handle both the high viscosity and the abrasiveness.

One important fact is that when CWF is injected into the boiler, it burns more like pulverized coal than oil; the water evaporates and the coal particles within the droplet fuse together. The volatiles are then burned off and the remaining carbon is ignited and burns.

The combustion and pumping characteristics of CWF are primarily controlled by the amount of coal and chemical additives in the fuel. Because the water in CWF actually consumes energy during the evaporation, thermal efficiency is improved by making the coal-to-water ratio as high as possible. However, a highly packed slurry is very difficult to pump and atomize. Therefore, chemicals that coat the coal particles and reduce the viscosity of the fuel are used. The size and amount of coal in the slurry are also regulated to provide the best balance between pumping/atomization and combustion. Appendix A contains a more detailed explanation of CWF characteristics and properties.

* A study report is in preparation.

3 CWF BOILER RETROFIT SYSTEM DESIGN AND OPERATING PROCEDURES

The system discussed in this section is intended for a typical Army steam boiler. The design is comprehensive and an accurate price estimate for implementation can be made from it.

Design Criteria

Design Life

The service life of this retrofit system is approximately 25 years.

Capacity

This retrofit is modeled for a 40,000-lb/hr steam boiler.

Design Assumptions

The boiler was assumed to have an output capacity of 40,000 lb/hr of 165 pounds per square inch atmosphere (psia) saturated steam with 175 °F boiler feedwater. The boiler efficiency was set at 80 percent. CWF consumption for a boiler operating at 40,000 lb/hr steam load is 5300 lb/hr or 8.74 gallons per minute (gpm). The combustion air required at this rate with 20 percent excess is 49,300 lb/hr or 10,750 actual cubic feet per minute (ACFM) at 60 °F. The flue gas flow generated at 20 percent excess air is 54,060 lb/hr or 18,300 ACFM at 350 °F. Mean gas velocities of 2500 ft/min and 3500 ft/min were used to size the air ducting and breeching, respectively.

System Design and Layout

The CWF retrofit system flowchart is shown in Figure 1. The equipment and piping layout of the CWF system is shown in Figure 2. The CWF boiler piping and installation design is shown in Figure 3. The CWF unloading and storage design is shown in Figure 4, and the CWF system control logic is shown in Figure 5.

Derating Potential of CWF

When a boiler originally designed for oil- or gas-firing is converted to CWF firing, its performance is adversely affected. There are three primary reasons for this. The first is furnace volume. Oil and gas burn almost instantaneously in a hot furnace. However coal, because of its slow-burning fixed carbon, requires more time to burn. Therefore, a furnace designed for gas or oil with a furnace retention time of 0.2 to 0.5 second is inadequate for a coal particle requiring approximately 1.0 second to completely burn. This problem is compounded by the higher excess air needed for coal. The second adverse condition arising from burning coal is slagging and fouling deposition on the furnace and convection tubes. Slagging and fouling deposits lower the thermal efficiency of the boiler and also lead to tube corrosion and failure. The last major problem with burning coal in oil and gas boilers is erosion. Fly ash in the flue gas erodes the convective tube section. To avoid excessive erosion, flue gas velocities are maintained at recommended values.

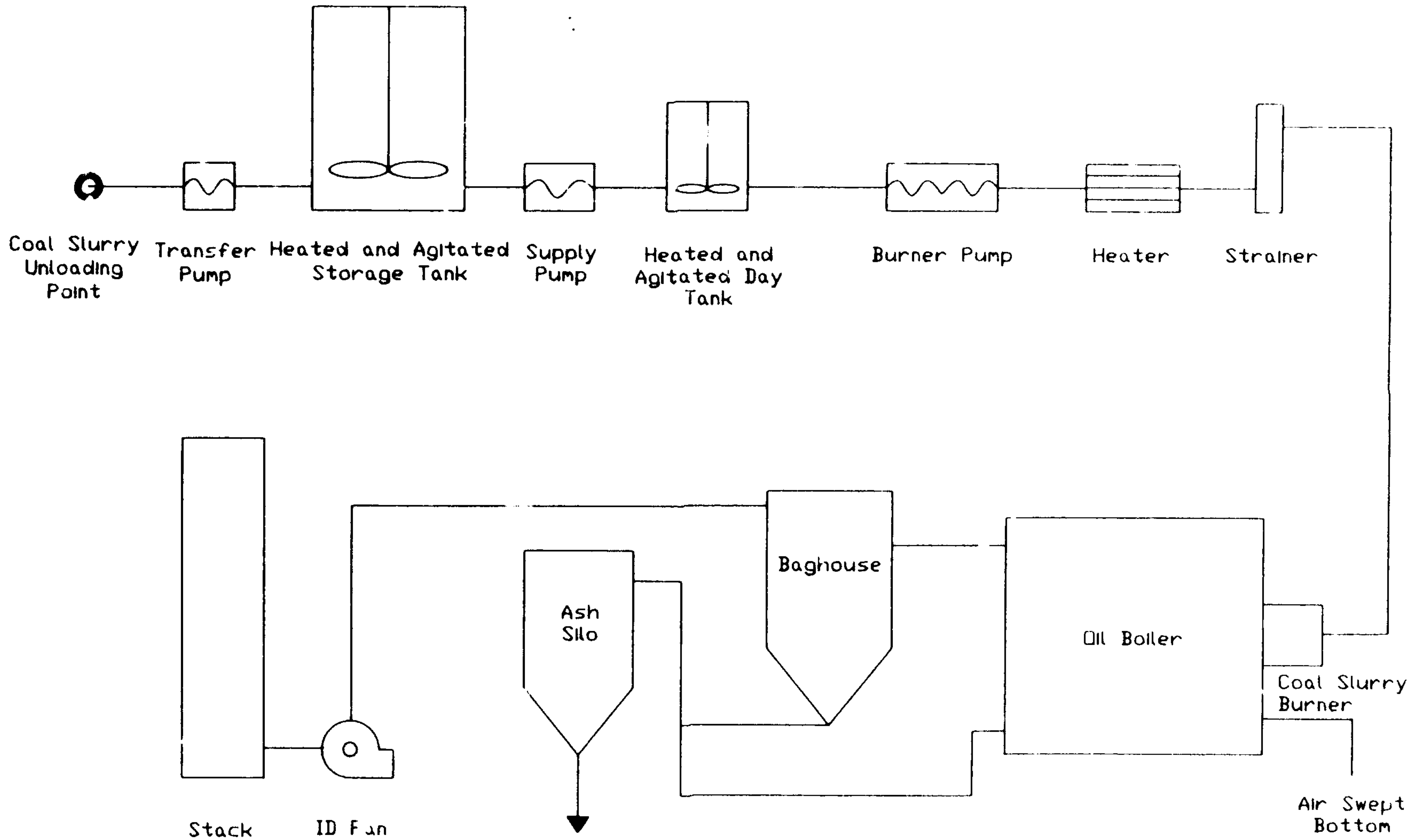

Figure 1. The CWF retrofit system.

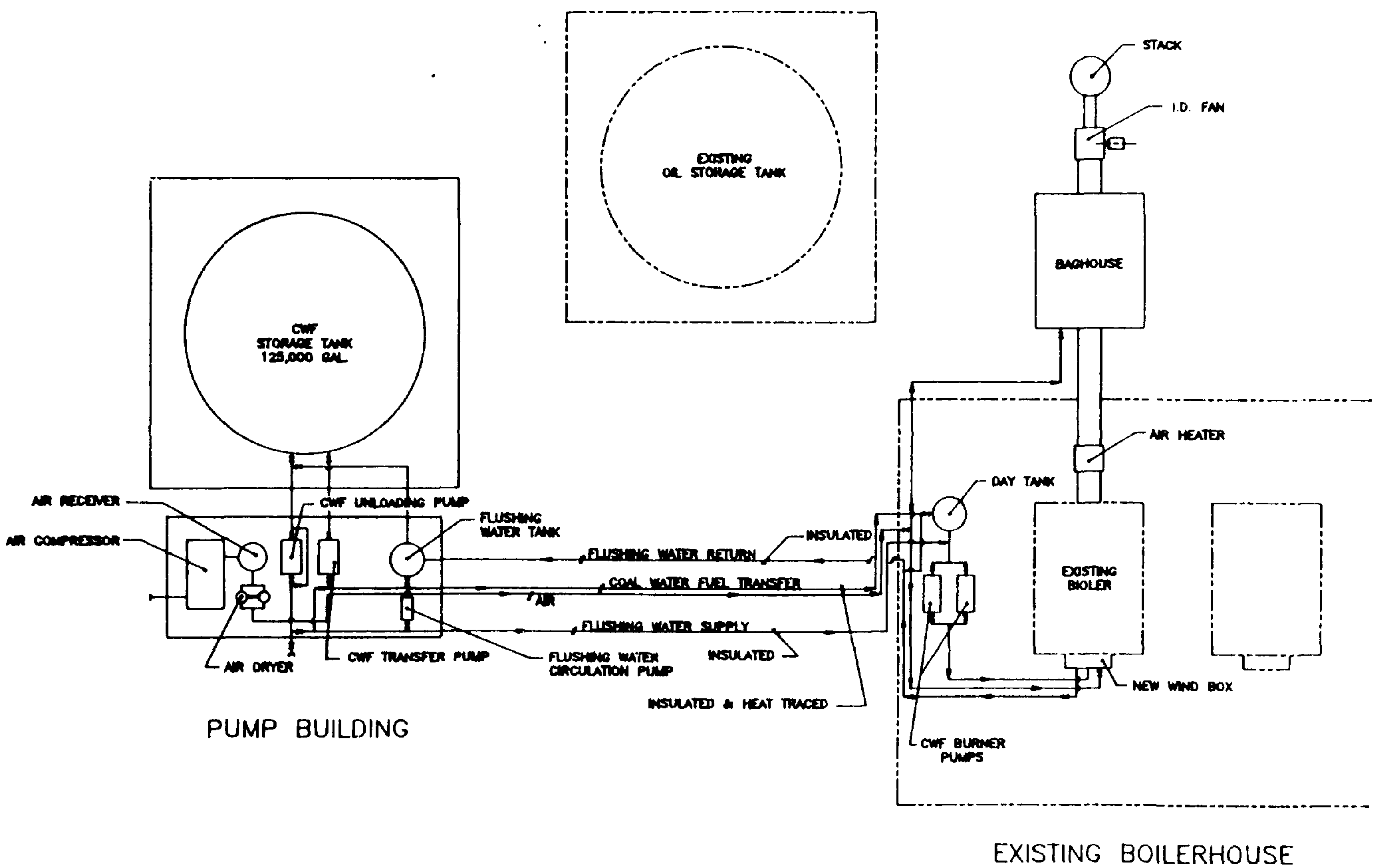

Figure 2. The CWF system equipment layout.

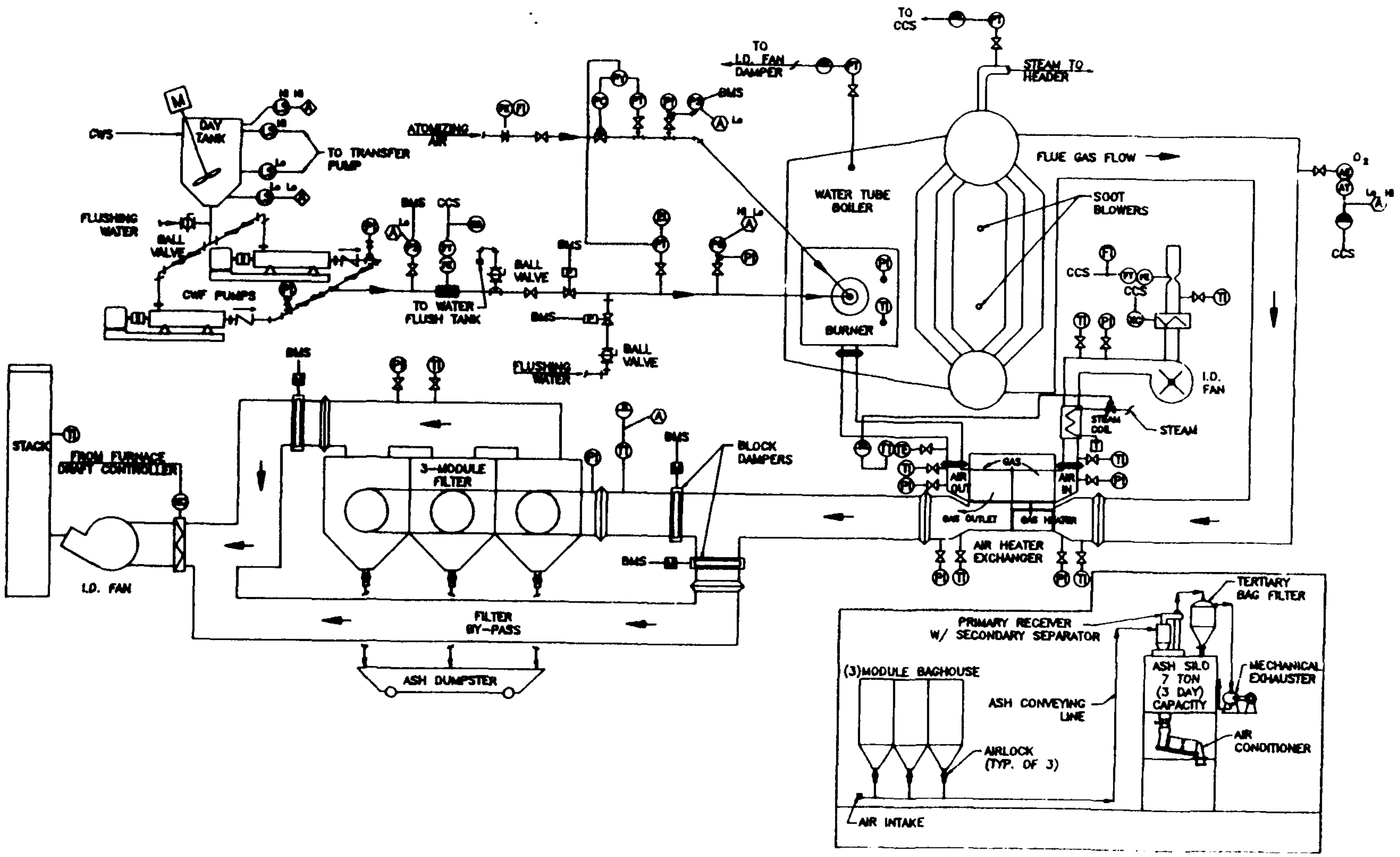

Figure 3. The CWF boiler piping and instrumentation

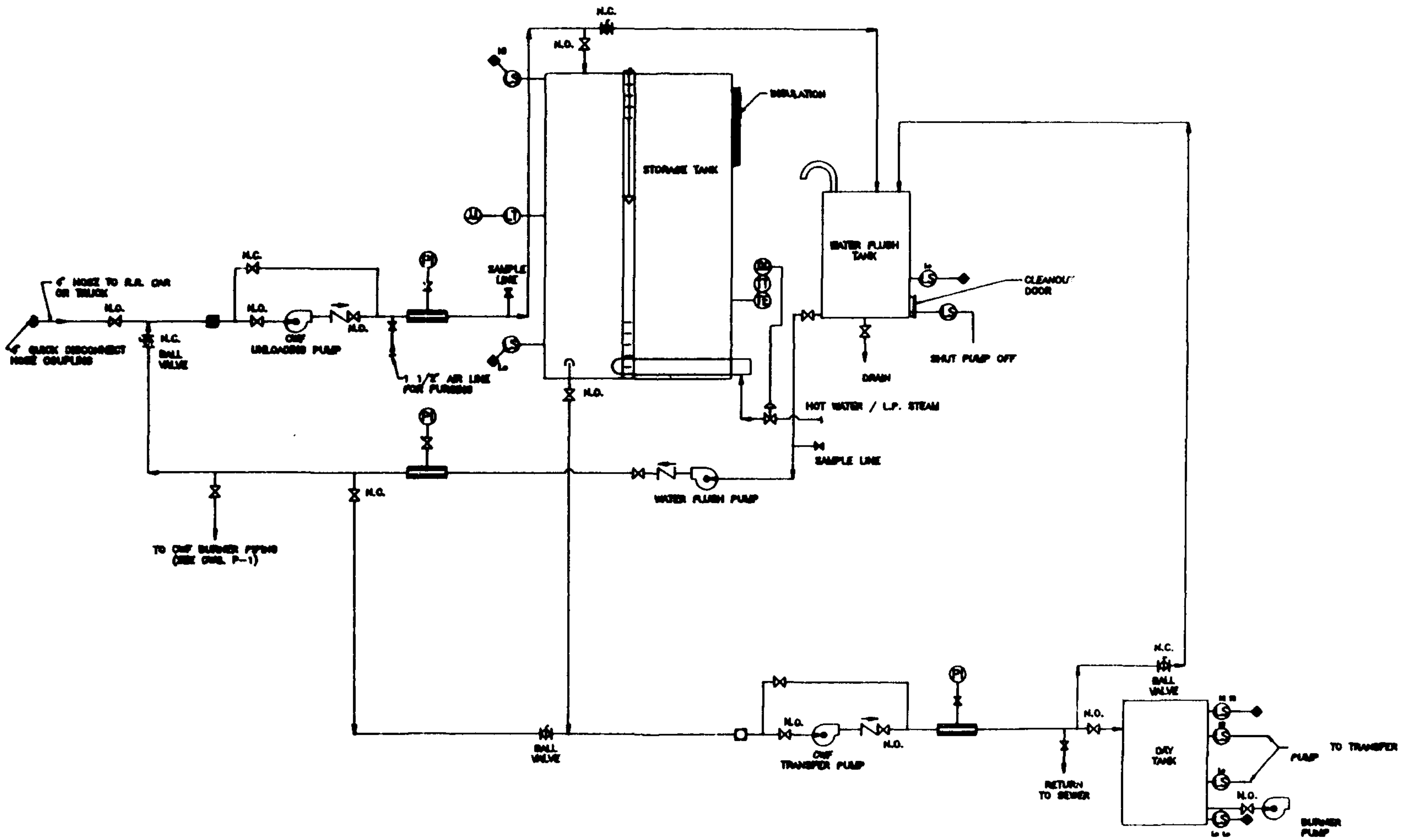

Figure 4. The CWF unloading and storage design.

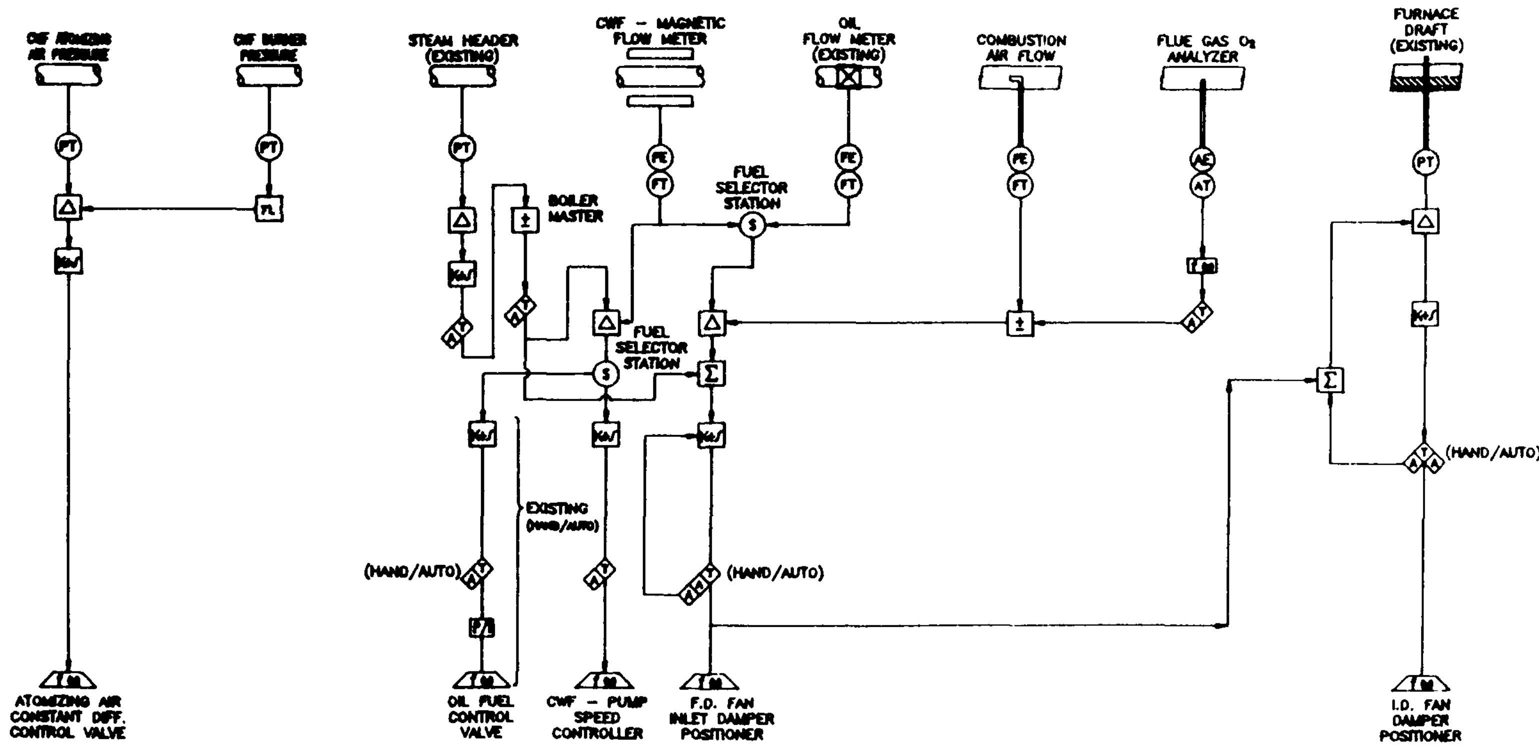

Figure 5. The CWF system control logic.

Several options are available to minimize the adverse effects of burning coal in oil and gas boilers. Required retention time can be reduced by decreasing the coal particle size, improving atomization, increasing the turbulence, or reducing the firing rate. Slagging and fouling deposition is not fully understood; many factors concerning the ash composition play a part. However, the easiest way to avoid slagging, and to a large extent fouling, is to keep the furnace exit gas temperature (FEGT) well below the initial ash deformation temperature. Historically, boiler manufacturers design for a FEGT of 200 to 300 °F below the ash initial deformation temperature. While there are several methods for controlling the FEGT, such as gas recirculation or changing the eff ve radiant heat transfer area, the easiest way to avoid a high FEGT is to reduce the burner firing rate. Erosion can be altered by changing the volume of fly ash or its composition, or by reducing the fly ash particle size so that the particle follows the gas flow around tubes. However, the easiest method for controlling erosion is to reduce the flue gas velocity by reducing the firing rate.

Table 1 gives a comparison of the three standard boiler designs. As shown, Keeler was used for the D type; Zurn for the O type, and Nebraska for the A type. The boiler model number, designed oil capacity, combined furnace and convective heating surface, furnace volume with approximate dimensions, and convective tube spacing are listed. From the given tube spacing, the tube-free area was estimated to calculate flue gas velocity through the tube section.

Table 2 can be used to analyze the suitability of a particular boiler type and to estimate the required derating. This table compares the furnace heat release rates and mean gas velocities for the different boiler types. The most significant conclusion that can be drawn from Table 2 is that the O type boiler manufactured by Zurn should not be considered for CWF retrofit. The furnace volume and convective tube spacing are inadequate to obtain an acceptable and economical steam output from an O boiler. The D and A types are comparable, with the D type having a slightly larger furnace volume and the A type a higher free tube area.

Using the data shown in Table 2 to estimate the required derating, the following calculation is made: 90 to 100 percent of the maximum continuous rating (MCR) of oil and gas burners can be obtained by firing CWF with acceptable mean flue gas velocities through the convective tube section (80 to 90 ft per second [fps]).. However, with these velocities, the volumetric heat release rates will be too high. Although the volumetric heat release rate is not a required design parameter with specific values to be observed, it is indicative of other factors, primarily the furnace retention time and the furnace exit gas temperature. To obtain a 1-second retention time in the Keeler D 50,000-lb/hr boilers, the CWF firing rate is 35,000 lb/hr, with a volumetric heat release rate of 38,000 Btu/cu ft/hour. At 85 percent MCR (42,500 lb/hr), the retention time is 0.89 second. These calculations were made assuming an average furnace temperature of 2400 °F and an effective furnace volume of 80 percent of the total furnace volume. Using the 1-second retention time as a limiting factor, the maximum rate obtainable with CWF is 70 percent MCR.

The FEGT is also affected by the furnace volumetric heat release rate; higher heat release rates result in a higher FEGT. The importance of the FEGT cannot be overstated. In most cases, it will be the limiting parameter. The FEGT should be limited to 100 °F below the coal's initial ash deformation temperature.

Flue gas velocities in oil and gas boilers normally range from 120 to as high as 200 fps. Normal coal firing practices limit the velocity to 60 fps with a high quality, low ash coal. However, with CWF, a maximum mean gas velocity of 85 to 90 fps can be tolerated due to the higher consistent coal quality and smaller particle size. In the final analysis, only actual field testing will determine the derating of an individual boiler. Field measurements of FEGT and carbon burnout will set the optimum performance point.

Table 1

Standard Oil - Advanced Technology Boiler Design Comparison Sheet

Keeler D Type

Model No.	Capacity (Oil) lb/hr	Heating Surface Sq Ft	Furnace Volume Cu Ft	Furnace Width	Furnace Length
DS-10-10	50,000	5489	1120	6 ft 4 in.	22 ft
DS-10-12	60,000	6478	1335	6 ft 4 in.	25 ft 6 in.
DS-10-14	70,000	7500	1550	6 ft 4 in.	30 ft
DS-10-20	80,000	8048	1465	6 ft 6 in.	28 ft
DS-10-21	90,000	8629	1570	6 ft 6 in.	30 ft
DS-10-21	100,000	9775	1790	6 ft 6 in.	34 ft.

Zurn O Type

Model No.*	Capacity (Oil) lb/hr	Heating Surface Sq Ft	Furnace Volume Cu Ft	Furnace Height	Furnace Width	Furnace Length
12 M	50,000	3183	770	5 ft 7 in.	7 ft 5-1/2 in.	17 ft 6 in.
13 M	60,000	3376	812	5 ft 7 in.	7 ft 5-1/2 in.	18 ft 6 in.
14 M	70,000	4647	971	5 ft 10 in.	8 ft 3 in.	18 ft 10 in.
15 M	80,000	5081	1053	5 ft 10 in.	8 ft 3 in.	20 ft 6 in.
16 M	90,000	5892	1324	6 ft 5 in.	8 ft 9 in.	22 ft 6 in.
17 M	100,000	6171	1380	6 ft 5 in.	8 ft 9 in.	23 ft 6 in.

Nebraska A Type

Model No.**	Capacity (Oil) lb/hr	Heating Surface Sq Ft	Furnace Volume Cu Ft	Furnace Height	Furnace Width	Furnace Length
N2S-4A-62	50,000	4693	1081	7 ft 4 in.	7 ft 2 in.	20 ft 4 in.
N2S-7-59	75,000	6096	1096	7 ft 10 in.	7 ft 2 in.	19 ft 4 in.
N2S-7-73	100,000	7335	1357	7 ft 10 in.	7 ft 2 in.	24 ft 2 in.

* Models 12M and 13M have two freestanding rows of 2-in. outside diameter (O.D.) tubes on 2-3/4 in. centers. Approximate free area = 5 sq ft. Models 14-17M have three freestanding rows of 2-in. O.D. tubes on 3-1/8 in. centers. Approximate free area = 11 sq ft.

** Model N2S-4A-62 has four freestanding rows of 2-in. O.D. tubes, for 17 sq ft area. Models N2S-7-59 and N2S-7-73 have six freestanding rows of 2-in. O.D. tubes for 24 sq ft area.

Table 2

Comparison of Derating Parameters

Furnace Heat Release*

Oil				CWS							
lb/hr	Btu/cu ft			lb/hr (85%)	Btu/cu ft			lb/hr (60%)	Btu/cu ft		
	D	O	A		D	O	A		D	O	A
50,000	52,521	76,394	54,416	42,500	45,276	67,310	47,945**	30,000	32,665	47,513	33,844
70,000	53,131	84,813	75,140	59,500	46,813	74,278	66,209	42,000	33,045	52,749	46,733
100,000	65,725	85,251	86,696	85,000	57,910	75,115	76,338	60,000	40,878	53,022	53,921

Mean Gas Velocity***

Oil				CWS							
lb/hr	ft/sec			lb/hr (85%)	ft/sec			lb/hr (60%)	ft/sec		
	D	O	A		D	O	A		D	O	A
50,000	53	201	59	42,500	53	202	59**	30,000	38	143	42
70,000	74	128	59	59,500	74	128	59	42,000	53	91	42
100,000	106	183	84	85,000	106	183	84	60,000	75	130	60

* Assuming 85 percent oil, 82 percent CWS boiler efficiency and 1000 Btu/lb enthalpy changes.

** Assuming 82 percent boiler efficiency, 1000 Btu/lb delta enthalpy, FEGT is 2200 °F (2400 °F oil), CWS Low Heating Value (LHV) is 9695 Btu/lb (17,500 oil) and 10.2 lb of flue gas per lb of CWB burned (15 lb oil).

*** Sample Calculations:

A. 50,000 pph x .85 MCR% x 1000 Btu/lb + .82 efficiency + 1081 ft^3 Volume = 47,945 Btu/ft^3 hr.

B. 50,000 pph x .85 MCR% x 1000 Btu/lb + .82 efficiency + 9695 Btu/Lb CWS = 5346 lb CWS/hr.
5346 lb/hr CWS x 10.2 lb F.G./lb CWS - 29 lb F.G. mole x 359 ft^3/mole
x (2200° + 460°)/492° R - 17 ft^2 free tube area + 3600 sec/hr
= 59.6 ft/sec

Equipment

CWF Unloading

The CWF storage facility is assumed to provide 10 day's storage of CWF, or 125,000 gal. Incoming CWF is unloaded into a CWF storage tank that is 35 ft in diameter by 20 ft high. Because CWF is denser than #6 oil, the tank is rated accordingly. Derating of a #6 oil tank is typically around 35 to 40 percent (25 to 50 percent range). CWF can be received by rail car or tanker truck. A CWF unloading pump with a capacity of 75 gpm is provided to allow suction through a 4-in., quick-connect hose fitting. The pump is operated manually and contains a bypass in case the rail car or tanker has its own pumping system. At 75 gpm, a 6000-gal tanker truck can be unloaded in 1-1/2 hours and a 20,000-gal rail car in 5 hours.

The storage tank is a carbon steel, fixed roof, atmospheric tank. The tank is insulated and equipped with a hot water heating coil to maintain the temperature between 90 and 100 °F. The liquid level is indicated by a float gauge and electronic level transmitter. High and low level switches with alarms are included. The tank is diked.

A high-pressure air connection is provided to clean the unloading line after a shipment. The air will move the bulk of the CWF into the tank before the line is flushed with water.

CWF is pumped from the storage tank to the day tank in the heat plant. The CWF transfer pump has a capacity of 35 gpm at 20 pounds per square inch gauge (psig) discharge. The pump can be operated in either a manual or automatic mode. In automatic, the pump is started and stopped by a set of level switches in the day tank. At 40,000 lb/hr steam load, the transfer pump will operate 15 minutes each hour. Operating this frequently will avoid settling problems with the CWF. The transfer piping from the storage tank to the transfer pump and day tank is insulated and heat traced.

The day tank is sized for 1500 gal, or 3 hr of CWF at 40,000 lb/hr steam load. In addition to the level switches that operate the transfer pump, the day tank also has a 100 revolutions per minute (rpm) mixer and a set of low and high level alarm switches. The mixer is included to allow water to be added in order to lower the CWF viscosity when needed.

CWF Burning

The day tank provides suction to the CWF burner pumps. There are two burner pumps; each is capable of operating at 40,000 lb/hr steam load. The capacity of each pump is 8.75 gpm, with variable speed motors as fuel control for the combustion control system. The discharge pressure of the CWF pumps is 180 psig to yield a burner pressure of 150 psig.

A single CWF burner is used and the existing oil burner system will be maintained. It is anticipated that a new windbox will be necessary with the CWF burner due to the increased volume of hot combustion air. A study of CWF burners indicated that Babcock and Wilcox and Combustion Engineering had the most successful burners.[3] Babcock and Wilcox uses a modified T-jet burner with air atomization. Combustion Engineering has a Y-jet using air or steam atomizing. Although no burner manufacturer is clearly superior, the cost estimate uses a Babcock and Wilcox burner.

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[3] P. Ramachandran, C. Y. Tsai, and G.W. Schanche, *An Evaluation of Coal Water Slurry Fuel Burners and Technology*, USACERL Technical Report E-91/07 (USACERL, July 1991).

The CWF burner will be ignited by the existing oil burner. A new flame scanner will be installed for the CWF flame. CWF atomization is achieved in this study with compressed air, however, steam atomization should be considered on a case-by-case basis.

Combustion air is provided by a forced draft fan sized for 20 percent excess air at full steam load. The fan is rated for 13,000 ACFM at 60 °F. The air is preheated with a steam coil to 200 °F before entering the air heater. The exit temperature of the air from the air heater is 375 °F.

Pollution Control

Flue gas will exit the boiler at approximately 520 °F at 54,100 lb/hr, will preheat the combustion air to 375 °F, and be cooled down to 350 °F. The flue gas at 350 °F is 18,300 ACFM and will be cleaned by a pulse jet baghouse sized at 3.0 ACFM per square foot of cloth gross and 4.5 ACFM per square foot of cloth net. The bags will be 16.5 oz/sq yd with a Teflon B finish. Flue gas is drawn through the baghouse by an induced draft (I.D.) fan located at grade. The I.D. fan discharges into a new 50-foot high stack.

Ash Handling

Because approximately 90 percent of all ash exits in the boiler as fly ash, no bottom ash removal system was incorporated into the design. A bottom ash removal system would be an unjustified expense. Bottom ash will be removed by hand several times per year while the boiler is cold. Fly ash will be removed from the convection tubes by soot blowing. All fly ash will be removed by the baghouse that will discharge the fly ash through a rotary seal into a dumpster where it will be manually wetted for disposal. At 40,000 lb/hr, 5 cu yd of fly ash will be collected per day.

A pneumatic conveying system can be used as an alternative to the manual fly ash disposal system. The ash will be conveyed pneumatically to the top of the ash silo, where ash is separated from the conveying air by a primary and secondary mechanical collector followed by a small baghouse. The ash is then deposited into the silo where it is removed by a rotary unloader, wetted and mixed before dumping into a truck. The ash silo has a 3-day storage capacity, or 500 cu ft.

Flushing Water

CWF cannot be left standing in piping for long periods of time, especially when exposed to heat. Settling will occur and result in scale forming on the pipe surface. This scale will not return to suspension when the flow is resumed. Because of this, a flushing water system is used. Four sections of piping should be flushed as needed. The first section is the CWF unloading line to the storage tank. The second section is the CWF transfer line from the transfer pump to the day tank. The third section is the CWF piping from the day tank to the burner management block valve. The fourth section is from the burner management system block valve through the CWF burner. The first three sections return the water to the flush tank, the last is evaporated in the boiler. The unloading line is flushed after each shipment, and the CWF burner line is flushed each time it is taken out of service. The other two piping sections are flushed as needed during long outages.

The flushing water circulation pump is operated manually. Each section of pipe is isolated by the operator. The flush tank will require periodic cleaning to remove sludge buildup. The tank has a level switch with an alarm and another level switch that shuts off the circulation pump.

Compressed Air

A compressed air system provides atomizing air to the CWF burner and pulsing air to the baghouse. The compressor has a capacity of 400 standard cubic feet per minute (SCFM); 60 SCFM for the baghouse and 340 SCFM for atomizing. The air will be delivered at 100 psig. The compressor is a nonlubricated reciprocating type. An air dryer dries the air to a -40 °F dew point.

Compressor/Pump Building

Since the CWF conversions will be made to boilers in existing heat plants, it was assumed that there would not be sufficient room for all of the new equipment. For that reason, a preengineered metal building will be erected to house the air compressor and dryer, the CWF unloading and transfer pumps, and the water flush tank and circulating pump.

Operation

Because the operation and maintenance of a CWF converted facility is very similar to an oil facility, no increase in operating personnel should be required. However, special care must be given to the following: (1) CWF temperature, (2) CWF pumping, (3) draft control, and (4) load.

CWF is more sensitive than oil to temperature extremes. CWF may freeze if it is maintained near the freezing temperature of water. If CWF is over-heated, the water phase may evaporate and produce a vapor lock in the piping. Therefore, it is very important to maintain the CWF in the temperature range specified for pumping and burning. The CWF lines should be purged if they are to stand idle. The lines must be cleared to prevent the coal from being overheated and caked by the pipe tracing.

The progressive cavity pumps normally used for CWF require a flooded suction to operate properly. If the suction is not well flooded, the outlet fuel pressure may pulsate and cause problems with flame stability and combustion efficiency. Also, the pumps may be damaged if they are allowed to run dry.

The CWF flame is not as stable as an oil or gas flame because of the water present and the combustion properties of coal. High excess air is more likely to blowout a CWF flame than an oil or gas flame. Therefore, the boiler draft controls must be sensitive to variation and not react too quickly to increasing air requirements.

As discussed earlier in the **Derating Potential of CWF** section, an oil or gas boiler will have to be derated when burning CWF. The amount of derating depends on the boiler and CWF properties. If the maximum continuous rating for the CWF-fired boiler is exceeded, the boiler may be damaged. The damage will be in the form of tube erosion, slagging, and fouling from the excessively high flow rates and the high FEGT.

Light-Off Procedure

The steps below should be followed when lighting a cold boiler. It is assumed that CWF has been supplied to the day tank.

1. Start oil pump and heater
2. Bypass the baghouse
3. Close forced draft (F.D.) fan damper to full close
4. Start the F.D. fan
5. Close I.D. fan damper to full close
6. Start I.D. fan
7. Load F.D. fan
8. Purge the boiler
9. When the purge is completed, verify that all fuel valves are closed
10. Set the F.D. fan to minimum flow
11. Start the oil burner
12. Heat up the boiler and raise the steam pressure to 50 to 60 psig
13. Water flush the CWF burner
14. Open the steam to the air heater steam coil and obtain a minimum 250 °F combustion air
15. Set the oil flame to minimum firing
16. Start the CWF burner pump and establish the CWF flame
17. Send the flue gas to baghouse
18. Load the boiler with CWF
19. Stop the oil flame
20. Set the fuel selector switch to CWF.

CWF Flame Failure

If the CWF flame scanner(s) detect CWF flame failure, the burner management system will sound an alarm, close the CWF block valve, and shut down the CWF burner pump.

The operator should:

1. Bypass the baghouse
2. Open the F.D. fan damper
3. Purge the boiler
4. Switch the fuel selector switch to oil
5. Start the oil pump and heater
6. Complete the purge
7. Close F.D. fan damper to minimum flow
8. Verify that fuel valves are closed and start the oil burner
9. Load the boiler with oil
10. Flush the CWF burner
11. Determine the cause of CWF flame failure
12. Reduce the oil to minimum firing
13. Start the CWF burner pump and CWF burner
14. Send the flue gas back to baghouse
15. Load the boiler with CWF
16. Stop the oil flame
17. Set the fuel selector switch to CWF.

Construction Cost Estimate

Table 3 is a summary of the construction cost for a CWF system based on the specifications in this chapter and the calculation in Appendix B. The total cost of the retrofit, including overhead, profit, engineering, and contingency is $1,867,458.

Table 3

CWF Retrofit Cost Summary*

Item	Material	Labor
Burner and burner system	73,500	$8900
Forced draft fan and steam coil	5700	2344
Air heater	36,500	5016
Combustion air ductwork	6562	6562
CWF burner pumps	17,324	1784
Combustion controls and instruments	51,965	103,930
Baghouse	252,000	60,000
Induced draft fan	21,756	2344
Breeching	12,212	12,212
Stack	12,500	12,500
Expansion joints	11,760	5880
Day tank and mixer	5515	500
CWF storage tank	47,525	47,525
CWF unloading and transfer pumps	9580	1784
Water flush tank and pump	3750	1448
Piping	16,592	14,372
Electrical	26,260	28,165
Compressor and air dryer	34,229	4360
Compressor/pump building	11,200	11,200
Structural	14,800	22,200
Insulation:		
Comb Air Duct - A/H Outlet to Windbox	1217	2839
Flue Gas Breeching Boiler Outlet to Stack	4150	9682
Pneumatic ash conveying	199,500	85,500
Subtotals	876,097	451,047
Subtotal of Material and Labor		1,327,144
Overhead and Profit (15 percent)		199,071
		1,562,215
Contingency and Engineering (20 percent)		305,243
Total Conversion Cost		$1,867,458

*In Fiscal Year 1987 dollars.

4 ENGINEERING AND ECONOMIC EVALUATION OF A CWF PRODUCTION FACILITY

The design developed for the cost model of a CWF production facility is intended to define the upper limit for CWF price at an Army facility. The specifications for the capacity of the model and the technology employed in preparing CWF are based on the needs and resources of a typical Army heat plant.

Design Criteria

Design Life

The service life of this facility is approximately 15 years.

Capacity

A survey of Army facilities indicated that the average annual energy required for a typical Army base having boilers that could be retrofitted to burn CWF is 150 MBtu/hr. Based on this energy requirement, the fuel production capacity of this plant is specified to be nominally 9.2 tons/hr (73,000 tons/yr) of 18 MBtu/ton CWF. This assumes a 70 percent coal loading in the slurry and a 24 hr/day, 330 days/yr operation with a 55 Hardgrove Grindability Index (HGI) coal.

Grinding

In developing a design for a CWF production facility, a median between good performance and low cost must be found. Grinding is the most expensive operational step and the cost of grinding generally increases with decreasing particle size. Therefore, an economic CWF specification would allow for the largest particle size that could maintain a stable flame, provide good carbon conversion, and produce small ash particles. Small ash particles are desired because they reduce tube erosion and facilitate the removal of bottom ash by allowing it to be blown up in the flue gas stream to then be removed by the air pollution control device. Because of this, the cost of a bottom ash removal system can be spared.

A literature search suggests that a utility grind specification of 99 percent < 50 mesh (297 microns) and 80 percent < 200 mesh (74 microns) would be successful for boiler applications.

A ball mill with a classifier has been selected to provide this grind. A ball mill can easily grind down to this size in a continuous mode with better reliability and lower cost than other grinding devices. A classifier is included to separate any particles over 20 mesh (840 microns) that may cause plugging of the CWF atomizer.

Additive Package

Anionic surfactants are generally cheaper then nonionic surfactants. However, the concentration of anionic surfactants must be carefully controlled because their dispersion capability decreases if they go into solution. Also, anionic surfactants should be customized to the specific coal being slurried.

In addition to the dispersant, ammonium hydroxide should be used to keep the pH of the slurry near 8.5. Formaldehyde should also be included in the additive package as a biocide to prevent coal

degradation. A stabilizer should be included to prevent settling. In an actual facility, the additive package would have to be determined experimentally, based on the type of coal and the anticipated storage time of the CWF. The stabilizer could be eliminated by using recirculation or agitation in the storage tanks and by not storing the CWF for long periods. The biocide could possibly be eliminated.

Coal

The coal used in CWF must be selected carefully. It must have a high Btu content to avoid derating and a high volatile content to provide good flame stability. The coal should have a low equilibrium moisture content as this type of coal is easier to slurry and produces a higher solids loading. It should also have an HGI of 55 or greater to maintain the design capacity of the grinding circuit. For the basic grinding design, which does not include coal cleaning, the coal must have a low ash content to produce good combustion and to reduce bottom ash accumulation.

A literature search indicates the following coal properties will provide good CWF combustion characteristics:

Energy Content: 13,500 Btu/lb or more on a dry basis
Volatile Matter: 30 percent or more on a dry mass basis
Ash Fusion Temperature: 2450 °F initial ash deformation (reducing)
Ash Content: 7 percent or less on a dry mass basis.

System Design and Layout

The flow chart in Figure 6 describes the CWF production system. The plant layout is shown in Figure 7.

Economics of CWF Production

The cost to produce CWF can be calculated based on the plant design developed previously. The cost is calculated for a base case as well as high and low cases that incorporate variations in the cost of coal, transportation, and chemical additives. The cost of CWF with a simple cleaning process is also included. In the development of these prices, the cost associated with derating and pollution control are not included.

A sensitivity analysis that relates the cost of CWF to coal and additive prices is included. The effect of scaling and the forecasted price of CWF (based on the escalation of coal and electricity prices) are considered.

Base Case

- A coal price of $28/ton (FOB, free-on-board, the cost at the mine) is used (based on a survey of spot market prices for the specified coal).

- A $13/ton transportation cost is assumed for rail transport up to 500 miles.

- The additive package cost is $0.35/MBtu.

- No coal cleaning is included.

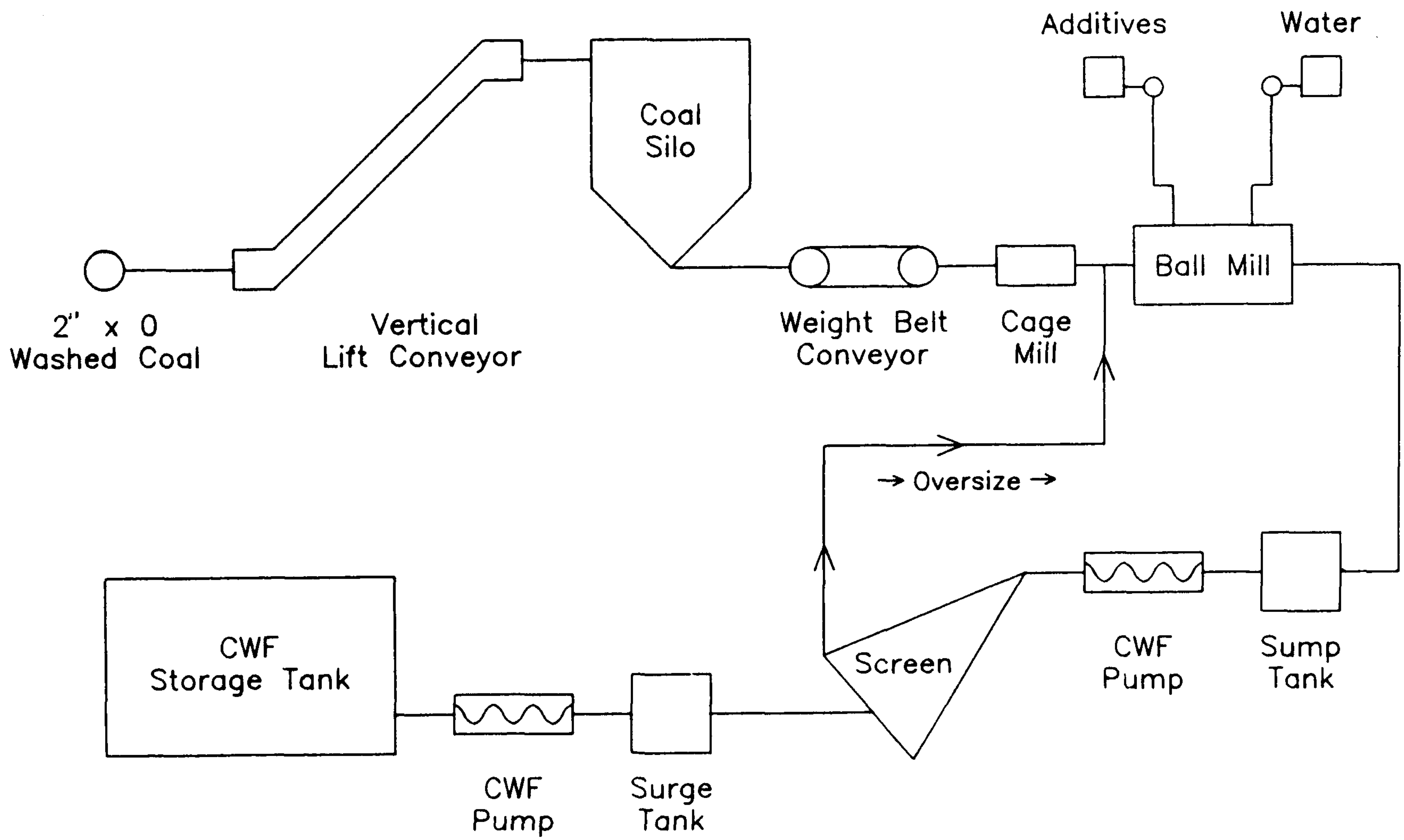

Figure 6. The CWF production facility flowchart.

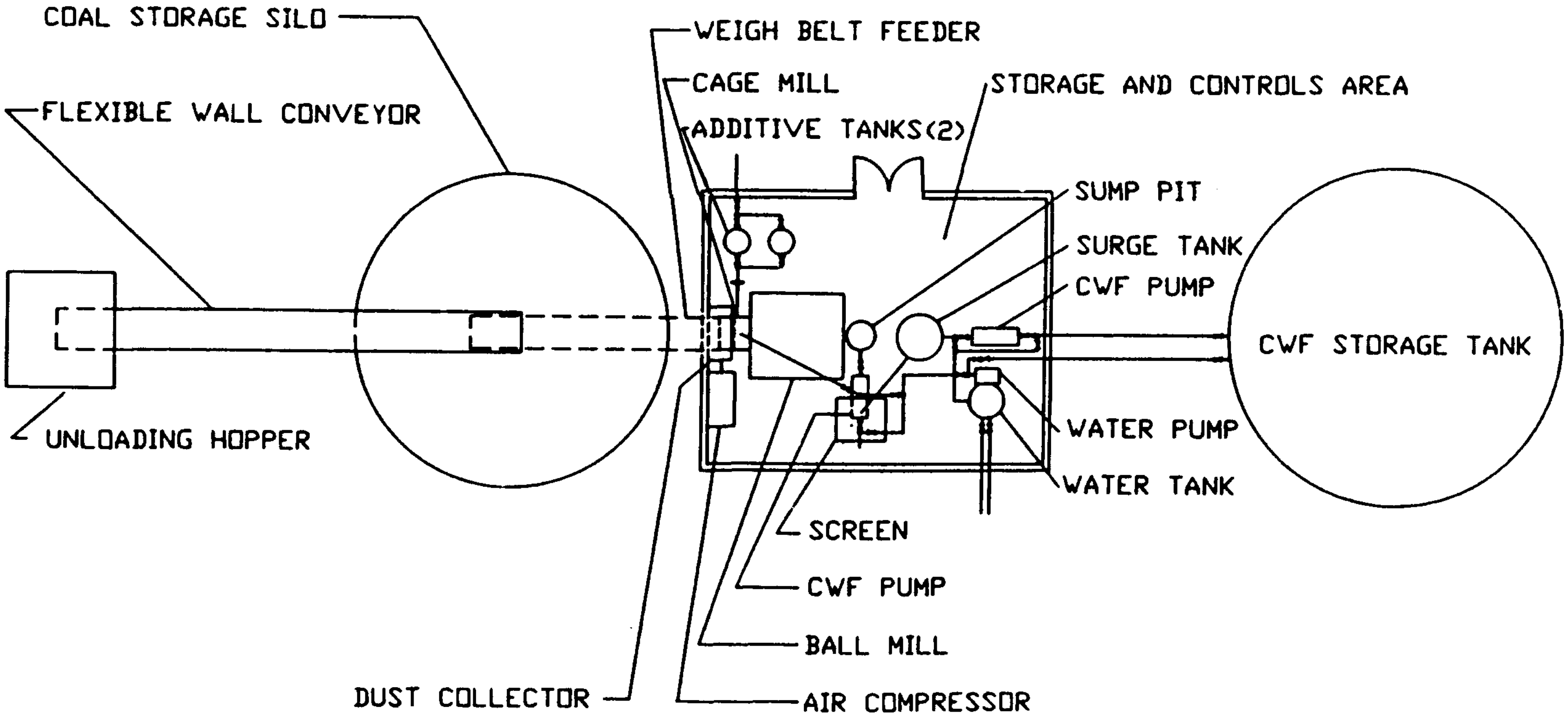

Figure 7. The CWF production facility.

Operation and Maintenance Cost. Based on the specifications and calculations in Appendix C, the operational and maintenance cost to produce CWF is \$3,435,421/yr or \$2.61/MBtu.

Capital Cost. Based on the design shown in Figures 6 and 7 and specified in Appendix D, the cost to construct the CWF production facility is \$1,678,021. The annual cost can be determined by:

$$A = Pd\,(1+d)^n/[(1+d)^n - 1] \qquad \text{[Eq 1]}$$

where A = annual cost
P = present cost (\$1,678,021)
n = design life (15 years)
d = discount factor (0.10).[4]

The annual cost would be \$220,616 or \$0.17/MBtu. The total cost would be \$2.78/MBtu.

Total Cost. Coal and transportation prices are based on the net available energy after water evaporates from CWF in the combustion zone.

\$1.09/MBtu coal at mine,

\$0.50/MBtu coal transportation,

\$1.19/MBtu slurry preparation.

The total cost of CWF is \$2.78/MBtu (Figure 8, case b).

Effect of Variations in the Price of Coal and Additives. Given an additive price of \$0.35 MBtu, the cost of CWF is strongly related to the price of delivered coal as shown in Figure 9. The price of the delivered coal has the biggest influence on the CWF price. Given a coal price of \$41/ton delivered, the cost of CWF is weakly related to the price of the additive package as shown in Figure 10. This relation shows that the price of CWF will not vary significantly with the chemical prices.

Range of CWF Cost

Low Cost Case. The low cost case assumes a \$20/ton (\$0.78/MBtu) coal cost at the mine, a \$10/ton coal transportation cost, and an additive cost of \$0.15/MBtu.

\$0.37/MBtu coal transportation,

\$0.99/MBtu slurry preparation.

The total cost is \$2.14/MBtu (Figure 8, case a).

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[4] Office of Management and Budget (OMB) Circular A-94 (Revised), *Discount Rates To Be Used in Evaluating Time-Distributed Costs and Benefits* (OMB, March 1972).

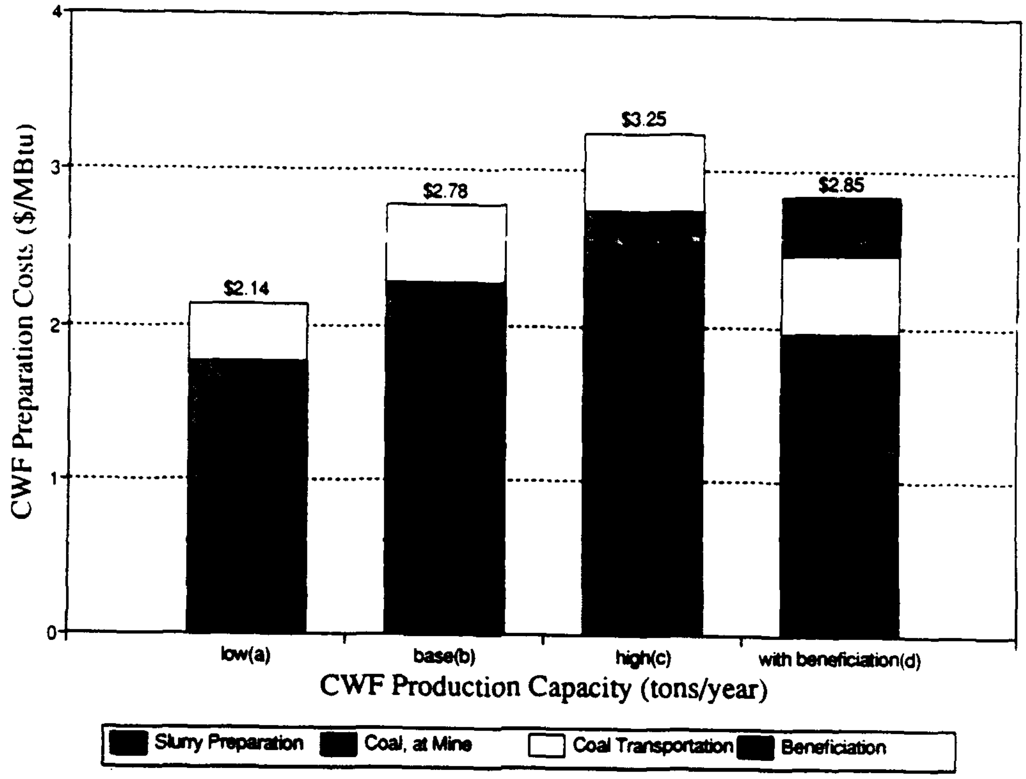

Figure 8. Cost of CWF.

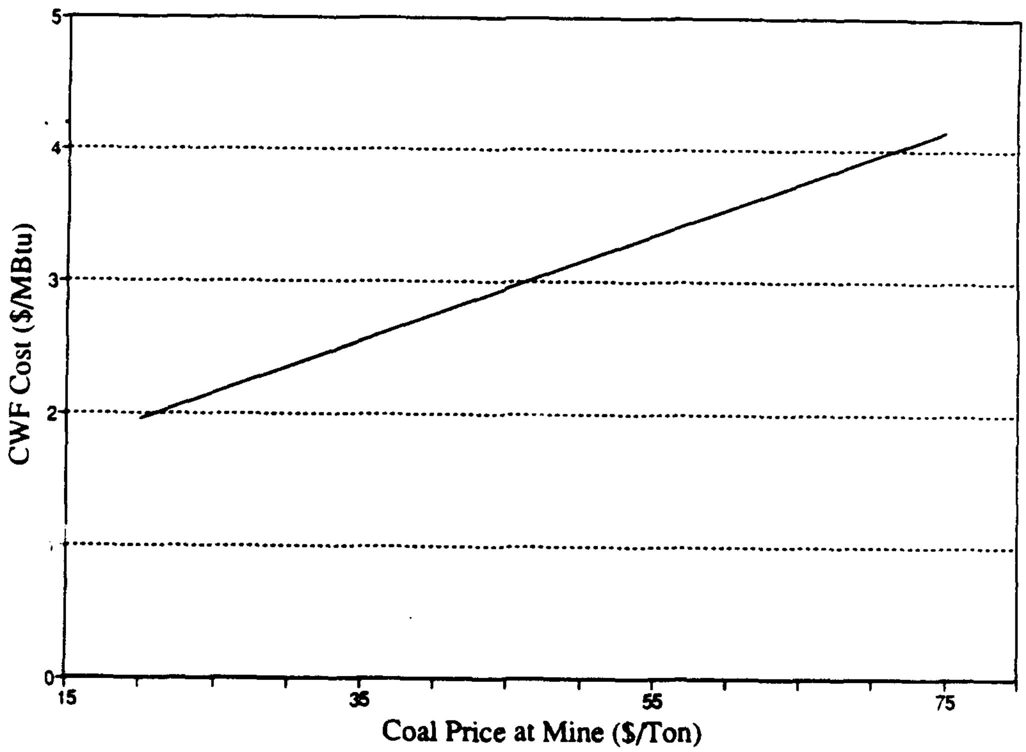

Figure 9. CWF cost versus coal price.

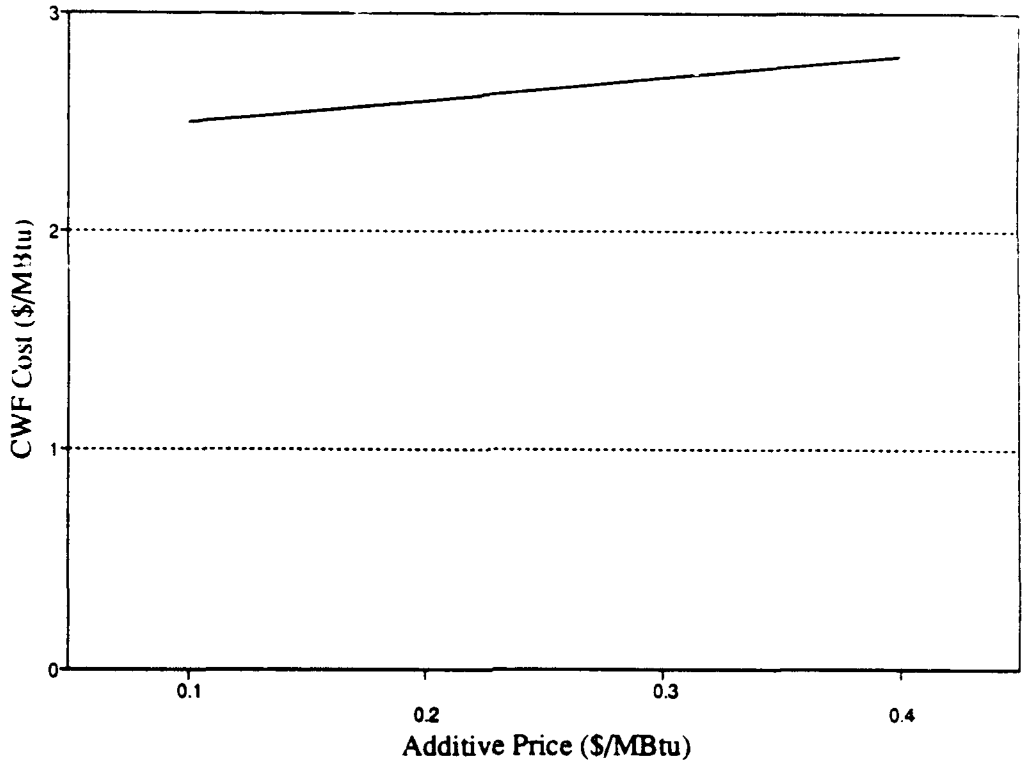

Figure 10. CWF cost versus additive price.

High Cost Case. The high cost case assumes a $40/ton ($1.56/MBtu) coal cost at the mine, a $13/ton coal transportation cost, and an additive cost of $0.35/MBtu.

$0.50/MBtu coal transportation,

$1.19/MBtu slurry preparation.

The total cost is $3.25/MBtu (Figure 8, case c).

Cost Including Coal Cleaning. The compatibility between coal cleaning and CWF may make CWF especially attractive in the future. Most cleaning processes are wet and result in a crude slurry. The added expense of drying is avoided when making CWF because additional water and stabilizers are included to make the final product. High ash coal is less expensive than low ash coal, therefore a $20/ton ($0.78/MBtu) coal cost at the mine is assumed in the cleaned coal case. The coal transportation and slurry preparation costs used are the same as the base case.

EPRI calculated the cost of simple physical cleaning to be typically $0.38/MBtu[5] and this value is used in this case.

$0.50/MBtu coal transportation,

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[5] T. Moore, "Oil's New Rival--Coal-Water Slurry for Utility Boilers," *EPRI Journal*, Vol 6, No. 13 (July/August, 1984).

$1.19/MBtu slurry preparation,

$0.38/MBtu coal cleaning.

The total cost is $2.85/MBtu (Figure 8, case d).

Scaling Economies

The effect of scaling is shown in Figure 11. The large scale case is based on slurry preparation costs for a 1,000,000 ton/yr plant.[6] Comparing this with the preparation cost calculated in this report for a small scale production facility (i.e., 73,000 ton/yr) the unit price of production increases with decreasing plant capacity as expected. The significance of scaling to Army heat plants is that the cost of CWF can be brought down if several facilities can be served from a large central production facility.

Forecasted Price

In qualitative terms, the cost of CWF relative to oil should decrease in the long term. This is primarily due to the steady price of coal in the face of anticipated increases in oil prices. In the short term however, it is difficult to quantify the cost differential between CWF and oil. Even though the future cost of CWF can be calculated fairly accurately, oil prices are unsteady.

Figure 12 shows the projected cost of CWF, oil, and natural gas (in 1987 dollars) to the year 2000. These costs are based on the average projected escalations in Department of Energy (DOE) regions 1 through 5 for coal and electricity given in DOE escalation tables.[7] These DOE regions encompass the eastern United States where bituminous coal is readily available. This projection indicates that CWF will be competitive, on a price basis, with #6 oil as early as 1992. In most areas, the potential price of CWF is currently lower than the price of natural gas.

A telephone survey of several potential CWF manufacturers indicated that several companies would be interested in the CWF market if the barrel price of oil rose to the mid-$20's. This is equivalent to approximately $3.00/MBtu which is projected by the year 1992.

[6] T. Moore.

[7] B. Lippiatt and R. Ruegg, *Energy Prices and Discount Factors for Life-Cycle Cost Analysis* (U.S. Department of Commerce, National Bureau of Standards, June 1987).

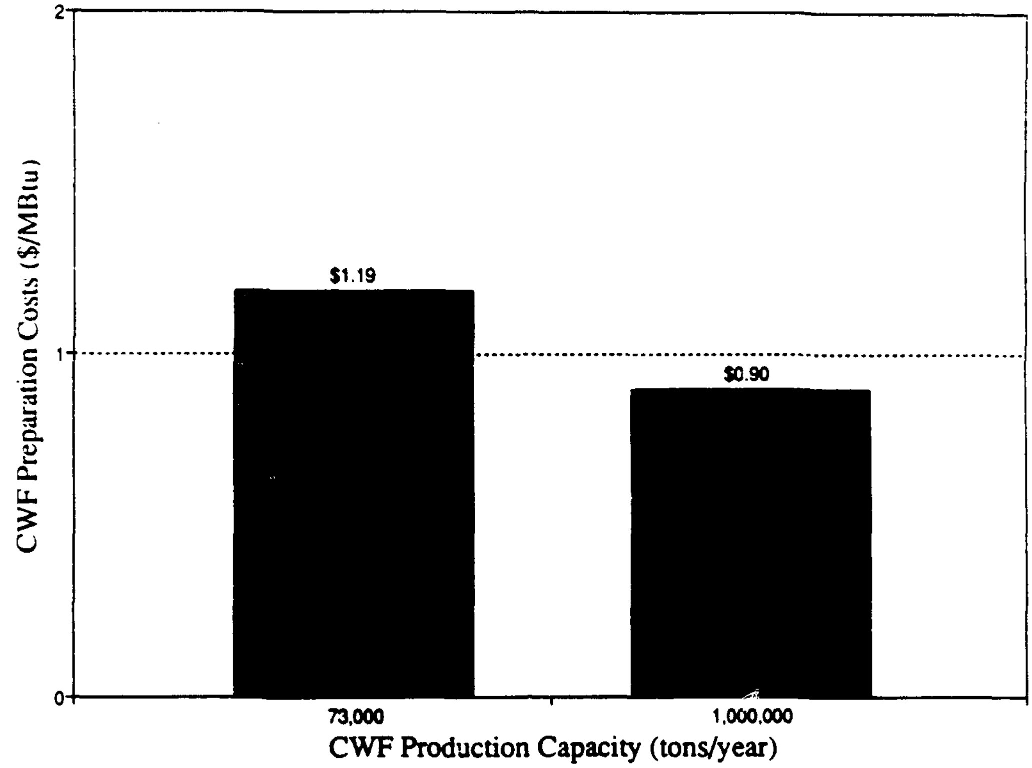

Figure 11. CWF preparation cost versus CWF production capacity.

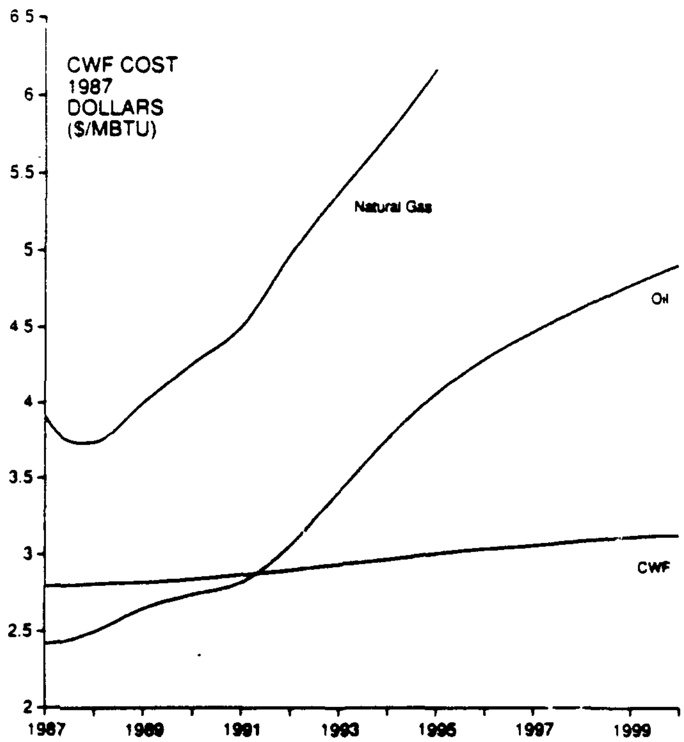

Figure 12. Future cost of CWF.

5 CONCLUSIONS AND RECOMMENDATION

Conclusions

This study indicated that CWF can cost as little as $2.61/MBtu and that an industrial sized oil-designed boiler can be retrofitted to burn CWF for approximately $1,867,458. Comparing this study's forecast for CWF price with the Department of Energy forecast for oil price suggests that CWF may be competitive with oil as early as 1992. The price of CWF is primarily controlled by the price of coal, which is stable and reliable.

Active research in coal cleaning holds promise of delivering effective and inexpensive methods of coal cleaning, allowing high ash and sulfur coals to be used in CWF. This broadens the supply of acceptable coal and, consequently, lowers the price. These factors make CWF attractive as a short and medium term, coal-based retrofit technology and as a long term technology for direct combustion of cleaned fuel.

The design developed here as a cost model for CWF production is intended for the near term implementation of CWF in a market where no large scale production facilities exist. Increasing the scale of the CWF production facility will lower the unit cost of CWF. However, this evaluation defines the upper limit for a simple CWF preparation cost as applied to an industrial size boiler retrofit.

Recommendation

Both the CWF production facility and the CWF boiler retrofit are based on assumptions that are intended to make them representative of a typical industrial scale heat plant. However, the design given in this report must be demonstrated before any large scale implementation should be considered. CWF should be demonstrated in a long term test program to determine equipment specifications, operational characteristics, systems controls requirements, and maintenance needs.

METRIC CONVERSION TABLE

1 cu ft/min	= 0.472 L/sec
1 ft	= 0.305 m
1 ft/min	= 0.305 m/min
1 fps	= 18.29 m/min
1 gal	= 3.78 L
1 lb	= 0.453 kg
1 ton (metric)	= 2,205 lb
1 ton (short)	= 0.9078 ton (metric)
1 ton (long)	= 1,016 kg
°C	= 0.55(°F - 32)

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APPENDIX A:

TECHNICAL BACKGROUND

Introduction

The first step in developing a CWF production facility is to specify a slurry composition that will economically achieve good combustion efficiency. Generally, increased combustion efficiency is associated with higher production costs. To understand the tradeoff between good combustion and good economics, an understanding of the combustion and rheology, or flow properties, of CWF is required.

Combustion

A small particle size is generally preferred for CWF because it promotes rapid combustion by giving more surface area for devolatilization and surface oxidation. This in turn improves the carbon conversion and overall combustion efficiency of the fuel. Rapid combustion is especially important in oil- and gas-designed boilers because they offer a much shorter residence time for combustion than do coal-designed units. In addition, smaller CWF particles will result in smaller ash particles which have less inertia in the flue gas stream. Therefore, the ash is more likely to follow the gas stream around tubing, which reduces erosion on the tubes. Once again, this is an important consideration for oil- and gas-designed boilers in which the tube spacing is narrower and the tube walls are thinner.

To take advantage of the small particle sizes in CWF, the atomizer droplet size must be matched to the slurry. They must be matched in the sense that the number of particles in the droplet should be minimized because they will agglomerate, or stick together due to the viscous forces of the melting coal. This reduces the effective surface area of the particles for oxidation.

Agglomerated particles commonly are produced during the combustion process in CWF burners. This combustion process involves the following steps, as shown in Figure A1. Initially, the water is vaporized. This consumes approximately 3 percent of the coal's energy in a highly loaded slurry (Figure A1 a). However, vaporization of the water also lowers the flame temperature, thereby reducing NOx formation. As the droplet heats up, the particles within it adhere due to surface and capillary forces. Once the outer layer of water is evaporated, the outer coal particles quickly heat up and agglomerate (Figure A1 b). Because the agglomerated particle is not heated uniformly, volatile evolution and subsequent ignition will occur at one point in the agglomerate and spread across the particle surface. With devolatilization, oxygen is displaced from the particle surfaces and a flame envelope forms around the particle. The soot formed by the cracking of hydrocarbons in the fuel-rich zone between the particle and the flame produces visible radiation and heats the char. Gases trapped within the agglomerate build up until there is sufficient pressure to blow through the surface. This process typically leaves a cenospheric (hollow sphere) char particle (Figure A1 c). As the particle becomes devolatilized, the flame envelope recedes until it is extinguished. When this occurs, oxygen can diffuse to the surface and into the pores of the char and oxidize it. When the oxidation reaction becomes fast enough, the char will ignite and the carbonaceous material is burned out. The resulting ash is usually cenospheric (Figure A1 d). The ash size is related to the size of the agglomerated particle which, in turn, corresponds to the droplet size. Cenospheric ash is less dense than typical coal ash.[1]

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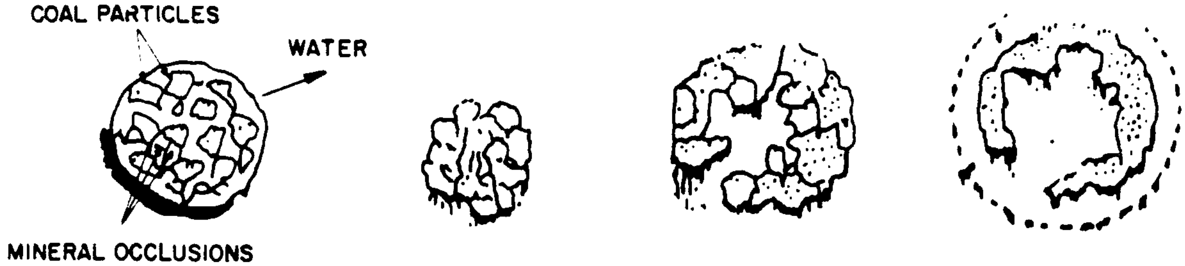
[1] S. Srinivasachar, et al., "Fundamentals of Coal-Water Fuel Combustion," *Proceedings of the 8th International Symposium on Coal Slurry Fuels Preparation and Utilization* (1986), pp 330-341; K. Matthews, and P. Street, "Combustion Histories of Various Coal-Water Fuels," *Proceedings of the 6th International Symposium on Coal Slurry Combustion and Technology* (1984), pp 109-126; M. Mulcahy, and I. Smith, "Kinetics of Combustion of Pulverized Fuel: A Review of Theory and Experiment," *Reviews of Pure and Applied Chemistry*, Vol 19 (1969).



Coal Water Slurry a | Dry Agglomerate b | Char Cenosphere c | Ash Particle d

Figure A1. The CWF combustion process.

The likelihood that the coal will agglomerate is related to the swelling characteristics of the coal, which is primarily a function of increasing vitrain concentration and the coal rank. Coals of either greater or lesser metamorphism than bituminous do not agglomerate as strongly.

If large agglomerates form within the droplet, the combustion advantage of a small particle size is negated because of the reduction of surface area available for oxidation. Therefore, the droplet size is the salient indicator of carbon conversion and combustion efficiency. Consequently, it is important to match the particle size to the size of the droplet produced by the atomizer. It is also important to have a high percentage of volatiles in the coal to provide rapid ignition and flame stability.

Rheology

Another consideration in specifying a slurry composition is to obtain the rheological properties desired for pumping and atomization. Unfortunately, the low viscosity desired for these purposes is the opposite of the high solids loading that is preferred to minimize the energy lost in transporting, heating, and evaporating the suspending liquid. Moreover, CWF rheology is generally thixotropic (viscosity reduction through agitation), pseudo-plastic (shear thinning) at shear rates over 10 sec^{-1},[2] and dilatant (shear thickening) at shear rates more than 10,000 sec^{-1}. This rheology makes it difficult to relate the easily measurable low shear rate viscosity to the high shear rate viscosity important in atomization.

Solids Loading

The intrinsic limit of the solids percentage of CWF is based on the geometry of the system. When there are too many solid particles in a slurry, the amount of liquid is insufficient to fill the interstices (spaces) between the particles. Consequently, the particles actually touch each other and the slurry becomes very dilatant at low shear rates, because of the frictional forces between the particles. A method

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[2] R. Kaji, et al., "Effect of Electrolytes on the Rheological Properties of Coal-Water Mixtures," *American Institute of Chemical Engineers Journal*, Vol 33, No. 1. (1987), pp 11-18.

to increase the solids loading is to switch from a monomodal system, where there is only one particle size, to a bimodal system that contains two particle sizes, the smaller of which is sized to fit the interstices of the larger particles.

This filling of the interstices by smaller particles can continue indefinitely, and the number of particle sizes used determines the modality of the slurry. In a close-packed, monomodal system of noninteracting spheres, a sphere with a diameter up to 0.125 times the large sphere diameters can move freely throughout the system and produce a bimodal slurry.[3] Coal particles are not spherical; therefore, the ratio of diameters constituting a bimodal composition, as determined above, is only an approximation. Typically, 0.10 is used as the ratio of the diameters.[4]

Coal Chemistry and Surfactants

The previous discussion provided insights on the upper limit of solids loading as defined by the geometry of the system. However, in most highly loaded slurries, surfactants are used to wet and disperse the coal particles in the supernatent liquid. Anionic and long polymer surfactants are used for this purpose. Anionic surfactants work by adsorbing on the coal surface and presenting their charged terminal group outward to form an electrostatic repulsion between similarly charged particles. Long polymers form a steric, or physical hindrance to flocculation (aggregation suspended in a fluid) by providing separation. In a CWF suspension using surfactants, the particles are subject to colloidal forces as well as hydrodynamic, gravitational, inertial, viscous, and thermal forces. The colloidal forces can be electrostatic, steric, and London/van der Waals forces. Hydrodynamic forces are the viscous drag of the supernatent liquid and the flow field disturbance created by a neighboring particle. Thermal forces are from molecular collisions. Inertial and viscous forces become more important with increasing particle size while colloidal forces become more important with decreasing particle size. CWF rheology is controlled by the balance of these forces.

The colloid chemical forces are affected by the surface properties of the coal and the ionic strength of the supernatent liquid. The hydrophobicity (water repelling property) of the coal determines how well the hydrophobic groups of the surfactants will adsorb to the coal surface and consequently disperse the particles. The aliphatic and aromatic carbons (fixed carbons) are the most hydrophobic constituents of coal.[5] The inorganic constituents of the coal are also hydrophobic but they can adversely affect the CWF dispersion by dissolving in the supernatent liquid and increasing the cations in solution. This neutralizes the electrical charge of the surfactants and decreases their dispersion ability. In addition, the multi-valent metals, particularly iron and calcium ions can form precipitates and can flocculate the coal particles.[6] Therefore, it is important to control the pH of the slurry as well as the quantity of the dispersant used in order to avoid saturating the surfaces of the coal and releasing the surfactants into the water.

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[3] R. Cadle, *Particle Size; Theory and Industrial Applications* (Reinhold Publishing Corp., 1965).

[4] C. Henderson, R. Scheffe, and E. McHale, "Coal Water Slurries--a Low Cost Liquid Fuel for Boilers," *Energy Progress*, Vol 3, No. 2 (1983), pp 69-75.

[5] E. Tour, et al., "The Effects of Aging and Oxidation of Powdered Coals Upon Coal-Water Slurry Properties," *Proceedings of the 8th International Symposium on Coal Slurry Fuels Preparation and Utilization* (1986), pp 1-9.

[6] E. Tour, et al.

DeVault and Associates[7] studied the factors that affect the slurryability of CWF. The study included identifying (1) the characteristics affecting the hydrophobicity of the coal surface: carbon/oxygen ratio, fixed carbon, fixed carbon/volatile matter ratio, free swelling index, natural pH of the coal, floatability, and percent of mineral matter, (2) the characteristics affecting the water absorption of the coal: pore volume/mass of coal, average pore diameter, reciprocal of water absorption, and equilibrium moisture, and (3) the characteristics related to the effectiveness of the dispersant: surface area available as measured by CO_2 and N_2 adsorption, specific adsorption area, and Hardgrove Grindability Index (HGI).

They found that the characteristics most strongly correlated with slurryability were equilibrium moisture, free swelling index, and floatability They found a weak correlation between slurryability and carbon to oxygen ratio and water absorption. The other parameters had weak correlations.

The equilibrium moisture of coal indicates the water absorption ability of the coal (an indication of how much water is absorbed in the coal matrix and consequently unavailable as supernatent liquid). The free swelling index gives a relative indication of the degree of coal oxidation. The slurryability increases with an increasing free swelling index. Floatability is based on indices developed by Sun[8] and indicates the hydrophobicity of the coal.

Particle Size

As explained in the discussion of the combustion characteristics of coal, a small particle size is desired to obtain complete carbon combustion. However, a large particle size is preferred for reducing the viscosity of CWF. Insights into the effect of particle size on rheology can be obtained by looking at noninteracting spheres. Sweeny and Geckler[9] performed an experiment in which glass spheres were suspending in an aqueous and nonaqueous medium of equal density (to avoid sedimentation). They found that viscosity increased greatly with decreasing particle size in the aqueous medium but was independent of particle size in the nonaqueous medium. They suggested that this relationship was due to the fact that in the aqueous medium, each glass sphere was surrounded by a layer of fluid which greatly increased its effective size. The resulting increase in volumetric concentration would be the largest for the smallest particle size.

This phenomenon is corroborated by CWF experiments. Tsai and Knell[10] determined the viscosity for compositions that approximated a monomodal system for two particle size ranges as well as for a bimodal composition over a wide shear rate. They found that the maximum volumetric loading was lower for the slurry with the smaller particle size.

In addition, both monomodal compositions are psuedo-plastic and the composition with the larger particle sizes had a lower viscosity to shear rate over 10 sec^{-1}.

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7 R. Devault, et al., Technical Paper RDTPA 85-34, *Characterization of Coals for Slurryability* (Babcock and Wilcox, 1985).

8 S. Sun, "Hypothesis for Different Floatabilities of Coals, Carbons, and Hydrocarbon Minerals," *Mining Engineering* (January 1954), pp 67-75.

9 K. Sweeny and R. Geckler, "The Rheology of Suspensions," *Journal of Applied Physics*, Vol 25, No. 9 (1954), pp 1135-1144.

10 S. Tsai and E. Knell, "Rheology and its Effects on Atomization of Coal Water Slurry," *Proceedings of the 1st Annual Pittsburgh Coal Conference* (1984), pp 190-200.

For a boiler retrofit application, a number of researchers have found that a particle size of 200 mesh (74 microns) is a good compromise between low viscosity, good combustion, flame stability, and economics. A 50 mesh (297 microns) is considered the maximum size that will burn at all in the short residence time provided in an oil-designed boiler.[11]

Particle Size Distribution

It is difficult to obtain an actual monomodal or bimodal composition in practice due to the grinding methods employed in CWF production and the fracture characteristics of coal. Typically, the final grind will produce particles over a range of sizes. Therefore, it is necessary to determine how slurries with distributed particle sizes behave.

As an extension of their work on the rheology of suspensions, Sweeny and Geckler[12] conducted an experiment using glass spheres to test the effect of particle size distribution on viscosity. Initially, they determined the size and shape of the interstices of a closely packed monomodal system. They found that two types of interstices were formed. The first (nearly cube shaped) can fit a sphere with a diameter up to 0.414 times the size of the spheres constituting the system. The second (similar to a tetrahedron) can accommodate a sphere with a diameter up to 0.225 times the size of the big spheres. They mixed spheres of various diameters into this system and measured the viscosity. First they used spheres that were too large to fill the cubic interstices, then spheres that were small enough to fill the cubic spaces, followed by spheres small enough to fill the tetrahedron shaped interstices, and finally spheres that could move freely through the system. This experiment indicated that the viscosity at rest increased a little initially when smaller particles were added (resulting in a greater diameter difference) and then decreased at higher shear rates.

This evidence suggests that a very wide particle size distribution will reduce the viscosity by increasing the modality of a slurry. Particles with smaller diameters will fill the interstices of the larger particles throughout the range of particle sizes. However, if there is a preponderance of a particular size, there may not be enough small particles to fill the interstices of the dominant particle size. In this case, a mixed composition results, with localized bimodal and monomodal groupings. In practice, a bimodal CWF is achieved by introducing a large quantity of micronized coal that is much smaller than the mass median diameter (mmd) of the supporting slurry. The smaller coal particles then fill the voids of the large slurry structure. Tsai and Knell's experiment[13] confirmed that viscosity is reduced in a bimodal CWF.

Although a wide particle distribution will give a lower viscosity, the most economical particle size distribution is based on an optimization of grinding, pumping, and atomization efficiency. Usually the particle size distribution resulting from the most economical grinding scheme must be accepted.

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[11] E. Knell, et al., "The OXCE Fuel Company Coal-Water Mixture Demonstration Project," *Proceedings of the 6th International Symposium on Coal Slurry Combustion and Technology* (1984), pp 976-981; R. Cadle.

[12] K. Sweeny and R. Geckler.

[13] S. Tsai and E. Knell.

Stability

To maintain a dispersed system, it is necessary to prevent external forces, such as gravity, from disturbing the CWF. Two consequences of instability are sedimentation and subsidence. Sedimentation is the settling motion of large particles relative to small ones which can appear in well disbursed slurries. Subsidence, on the other hand, is the settling motion of all particles relative to the supernatent liquid. This phenomenon occurs in slurries with some flocculation.

To provide stability, a gelatin stabilizer is added to the CWF to give a yield strength sufficiently high that the slurry will not move until a large shear stress is applied (Bingham plastic yield point). The value of the yield stress required to settle a particle can be calculated as a function of particle diameter, density, and suspending fluid density.

The yield point that must be produced by the stabilizer increases with increasing particle size, density, and external acceleration.

The desired yield point is one that is high enough to prevent settling of the largest particles but not high enough to cause excessive gelation. Stabilizers only affect low shear rate viscosity; at high shear rates their influence disappears.

Atomization

The atomization ability of CWF is one of the most important characteristics of the fuel because it controls carbon conversion efficiency. This characteristic is difficult to predict but a reasonable correlation has been made based on unpublished experiments by T. Yu, S. Kang, and J. Beer. They found that the mmd of the CWF droplets was a function of the Weber number, the Reynolds number, and the fuel-to-air ratio. The Weber number is the ratio of inertial forces to surface tension forces and the Reynolds number is a ratio of inertial forces to viscous forces. This correlation also suggests that the droplet mmd varies linearly with high shear rate viscosity. As mentioned previously, the rheology of CWF is difficult to predict and hence these relationships are difficult to use in practice. Experiments by Matthews and Street[14] underscored the importance of understanding the relationship between droplet size and viscosity. They found that the carbon conversion of CWF was highest with a solids loading of 62 percent. The carbon conversion decreased with more highly loaded slurries due to their increased viscosity. The carbon conversion also decreased with slurries under 62 percent because of the lower flame temperature resulting from the evaporation of the water.

A bimodal composition is more difficult to atomize than a monomodal one because of the stronger London/van der Waals forces and hydrogen bonds within the structure. The forces and bonds are stronger than usual because of the close proximity and large surface areas available on the fine particles.

This phenomenon is observed in the work by Tsai and Knell[15] in which the droplet mmd produced by a bimodal slurry is larger than that produced by a monomodal slurry. In addition, the atomization energy required was higher for the bimodal slurry.

[14] K. Matthews and P. Street.

[15] S. Tsai and E. Knell.

Dispersions after the atomizer, known as secondary atomization, are helpful in taking advantage of the small particle sizes originally contained in the slurry by breaking up the agglomerate in the injected droplet. When the agglomerate produced during the heating of CWF is broken up or fragmented, more surface area is available for oxidation. This produces more rapid combustion and smaller ash particles. One of the easier methods to achieve some degree of secondary atomization is to preheat the fuel so that upon injection, the center of the droplet will be heated quickly, relative to the surface. Consequently, the water throughout the droplet will vaporize causing the droplet to explode. Other techniques, such as the use of very high air to fuel ratios, high heat transfer rates to the droplet, methanol mixes, and pulse drying injection are currently being investigated.

CWF Burners

Many burners have been developed to burn CWF. The two biggest problems with burning CWF are flame stability and erosion of the burner. Standard alloy atomizers will become highly eroded in less than 100 hours due to the abrasiveness of the slurry. Tungsten carbide has been used as inserts in atomizers as well as to fabricate entire atomizers. Although tungsten carbide is resistant to CWF abrasion for the 2,000 hours considered commercially acceptable, there are still some problems. Inserts only transfer the erosion problem to another part of the atomizer, such as the mixing chamber. Therefore a balance has to be found between the cost of the inserts and the longevity of the burner. With both inserts and monolithic atomizers, heat transfer between the tungsten carbide and the steel must be good. If heat transfer is impeded by the method used to attach the two metals, the tungsten carbide will get very hot and coke the CWF.

The air registers must also provide a great deal of secondary air swirl to maintain flame stability. This swirling air produces an area of low pressure around the atomizer, setting up a recirculation of hot gases. The hot gas heats up the unignited CWF so that the water is evaporated and the coal devolatilized. This preheating of the CWF spray can also be assisted by using a refractory-lined, divergent throat (quarl) that absorbs the furnace heat and irradiates the CWF spray.

APPENDIX B:

EQUIPMENT LIST AND COST ESTIMATE

Burner and Burner Management Systen

For this study, it was assumed that the existing windbox would be replaced with the new burner. The burner system is capable of 100 percent firing on CWF or oil; however, dual firing is not possible. The oil burner system will not be modified. CWF will be ignite by an oil flame.

The system requires one CWF Burner (55MBtu/hr) with:

- Windbox
- Atomizer with Spare Tips
- Flexible Metal Hoses
- Throat Tile or Refractory

The estimated cost (Based on Babcox and Wilcox Burner) is:

• Material	$72,777
• Installation	$8,900
• Freight	$1,500

Forced Draft Fan for Combustion Air

The system requires inlet air at 60 °F for a capacity (net) of 13,000 ACFM. It is rated for 20 percent excess air at 40,000 lb/hr steam load.

A steam coil is needed on the fan discharge to preheat air to obtain a final air temperature of 375 °F. Air is preheated to approximately 200 °F by steam coil.

Bearings on the fan housing are also required.

The static pressure, net conditions, are listed below in inches of water:

Windbox	4.00
Air Heater	2.50
Ductwork	0.52
Steam Coil	1.00
Total	8.02

APPENDIX C:

OPERATIONAL AND MATERIAL COSTS

Operational Labor

Employees Required

a. (1) Foreman and Operator: operates and supervises facility.

b. (1) Maintenance Person: maintains facility equipment.

c. (1) Maintenance Assistant: assists in coal unloading and maintenance.

Billing Rate

From the General Wage Determinations Issued Under the Davis-Bacon and Related Acts.

a. $21.80/hr + 27 percent overhead = $26.16/hr.

b. $21.80/hr + 27 percent overhead = $26.16/hr.

c. $17.72/hr + 27 percent overhead = $21.26/hr.

Shift Schedule

a. (3) 8 hour shifts, 7 days/wk.

b. (3) 8 hour shifts, 7 days/wk.

c. (1) 8 hour shift, 5 days/wk.

Total Cost: = $501,288/yr.

Coal

High Btu, high volatile, low ash, low sulfur, sized bituminus coal. Transportation price is based on rail delivery up to 500 miles.

Coal: $28/ton at mine.

Transportation: $13/ton.

Total Cost: = $2,091,196/yr.

Water

Quantity: = 701,700 cu ft/yr.

Rate: $ 0.530/100 cu ft.

Total Cost: = $3,719/yr.

Additives

Dispersants: Pfizer Flosperse 370X at 2-3000 ppm

Stabilizer: Pfizer Flocon 4800c (xanthan bipolymer) at 150-250 ppm

pH Control: Ammonium hydroxide to maintain a pH of 8.5

Biocide: Formaldehyde to prevent coal degradation at 1000 ppm

Package Cost: 0.35 $/MBtu

Total Cost: = $459,000/yr

Electricity

Assumptions:

1. The efficiency of an electric motor is approximately 96 percent.

2. The base horsepower (bhp) used to calculate steady state energy consumption is 90 percent of the rated horsepower (hp) unless otherwise indicated.

3. $0.068/kWh

4. $12/kWh-month

5. hp = 0.7457 kW

Grinding System

Components:

(1) 1 hp weigh feeder
(1) 60 hp cage mill
(1) 600 hp ball mill
Total = 661 hp

Operating Schedule: 24 hr/day, 330 days/yr.

Usage Cost: = $248,276/yr.

Demand Cost: = $66,384/yr.

Total Cost: = $314,660/yr.

Coal Handling

Components:

(1) 200 hp belt conveyor
(1) 50 hp self feeder
Total = 250 hp

50 percent of rated hp is used at steady state.

Operating Schedule: 2 hr/day, 330 days/yr.

Usage Cost: = $4,353/yr.

Demand Cost: = $13,968/yr.

Total Cost: = $18,321/yr.

Pumping

Components:

(1) 5 hp progressive cavity pump
(1) 7.5 hp progressive cavity pump
(1) 5 hp centrifugal water pump
Total = 17.5 hp

Operating Schedule: 24 hr/day, 330 days/yr.

Usage Cost: = $6,463/yr.

Demand Cost: = $2,520/yr.

Total Cost: = $8,983/yr.

Air Compressor

Provides 3 cfm to dust collector. Energy cost is negligible.

Total Electrical Cost: = $341,964/yr.

Operating and Maintenance Supplies

This category includes replacement of wearing parts, lubrication, etc.

$0.75/ton of dry coal (assumed)

Total Cost: = $38,254/yr.

Total Operational and Material Cost: $3,435,421/yr.

APPENDIX D:

EQUIPMENT SIZING AND COST

Coal Handling

Train unloading facility with a Capstan car mover (sized for 15 cars), dump pit hoppers, "Flexowall" belt conveyor system from output of feeders to a 38-ft diameter by 96-ft high silo, and a weigh belt feeder. The silo will have a capacity of 2125 tons (14 day supply) and a hopper bottom. Also included are the sensors, controls, and the chute work at all transfer points.

The capacity of the system from the trains to the silos will be 75 tons per hour (tph) of coal. The capacity from the silos to the cage mill will be 6.5 tph.

Cost:	Material, Freight, and Installation	$1,717,333
	Foundation	$70,000
	Total	$1,787,333

Slurry Preparation

An open loop, wet grinding process is specified. Included is a 60 hp cage mill, 600 hp ball mill with charge and high lift pumps for bearing lubrication, slurry tank with agitator, and an additive pump. All motors are included. This circuit will have a nominal slurry production capacity of 10 tph and the viscosity of the slurry in the ball mill must be 1500 cp or less.

Cost:	Material	$60,000
	Freight	$3000
	Installation	$45,000
	Total	$108,000

Dust Collector

A dust collector is required at the cage mill. The dust will be returned to the ball mill. This baghouse uses 10-ft bags and requires 3 cfm of compressed air for cleaning. The material price includes the collector and support stand. The duct work also includes an exhaust chimney.

Cost:	Material	$9000
	Duct work	$2000
	Freight	$1000
	Installation	$2240
	Total	$14,240

Air Compressor

A portable air compressor (hose included) is specified to clean the bags in the dust collector. This unit has a 5-hp motor, a 30-gal tank, and is rated at 40 to 90 psig, delivering 12 cfm at 40 psi.

Cost:	Material	$700
	Freight	$50
	Installation	$25
	Total	$775

Safety Screen

A safety screen should be provided at the outlet of the slurry tank to control oversize particles. It will feed particles 20 mesh or larger back to the ball mill input via gravity through a 2-in. Schedule 40 pipe. A cyclone may be used in lieu of the safety screen to control top size.

Cost:	Material	$24,883
	Freight	$1200
	Installation	$1226
	Pipe installed $13.02/linear ft x 25 ft =	$326
	Gate Valve installed, 1 required	$162
	45 Elbow installed, 1 required	$10
	Reducing "T" Connector, installed, 1 required	$83
	Total	$27,890

Slurry Pumps

Four progressive cavity pumps are specified. Two 30-gpm variable speed pumps with 53 psig discharge pressure are required from the sump unit at the outlet of the ball mill to the safety screen. Two 30-gpm variable speed pumps with 124 psig discharge pressure are required from the 1000-gal surge tank to the CWF silo. The standby pump for the discharge of the 1000-gal surge tank can be used to recirculate the CWF in the storage tank and pipes if necessary. Additional piping would be required to provide recirculation.

Cost:	Material	$33,470
	Freight	$800
	Installation	$3356
	Total	$37,626

Slurry Storage

A 3500-ton (16-day capacity) CWF storage facility is required. This will consist of one 40-ft diameter by 72-ft high, post tensioned, concrete silo and roof with heating and insulation.

Cost:	Material, Freight, and Installation	$300,000
	Foundation	$27,500
	Total	$327,500

CWF Piping

2-in. Schedule 40 pipe with 1 in. insulated to the CWF storage silo. Some form of tracing will be required on exterior piping.

Cost:	Material and Installation	
	Pipe, installed $13.02/ln ft x 130ft =	$1693
	Insulation, installed $5.31/ln ft x 90ft =	$478
	Pipe supports, installed, 13 required	
	13 x $50 =	$650
	Pipe flanges, installed, 13 required	
	13 x $41.70 =	$542
	Duplex strainer, installed, 1 required	$1830
	Gate valves, installed, 9 required	
	9 x $161.70 =	$1455
	Swing check valve, installed, 2 required	$236
	90 elbows, installed, 8 required	
	8 x $23.80 =	$190
	"T" Connectors, installed, 4 required	
	4 x $38.50 =	$154
	Reducing "T" Connectors, installed, 4 required	
	4 x $83.17 =	$332
	Total	$7560

Controls

All slurry operations have automatic controls. This price includes all transducers, level switches, alarms, and the additive metering pump.

Cost:	Material and Installation	$50,000

Water Flush Tank

A 500-gal (52-in. diameter by 60-in. high) one-piece, molded polyethylene water tank with four 1-1/2-in. welded-in couplings is specified to collect water for the water flushing system.

Cost:	Material	
	Tank	$696.55
	Couplings, 4 required 4 x $52.90 =	$211.60
	Freight	$300
	Installation	$339
	Total	$1547

Water Flush Pump

A centrifugal 50-gpm, 50 psig pump with a 5-hp drive is specified to flush the CWF piping. The pump will be manually operated with a low level shutdown from the water flush tank.

Cost:	Material	$1250
	Freight	$100
	Installation	$113
	Total	$1463

Flushing Water Piping

1-1/2 in. Schedule 40 pipe with 1 in. insulation to the CWF storage silo. Some form of tracing will be required on exterior pipe.

Cost:	Material and Installation	
	Pipe, installed with hangers	
	$10.78/ln ft x 157ft =	$1692
	Insulation, installed $4.76/ln ft x 90ft =	$428
	Gate Valves, installed, 6 required	
	6 x $78.10 =	$469
	90 Elbows, installed, 5 required	
	5 x $10.70 =	$54
	"T" Connectors, installed, 3 required	
	3 x $15.60 =	$47
	Check Valve	39
	Total	$2729

Building

A 30- by 40-ft building with a 30-ft ceiling is specified for the slurry production facility. The 30-ft ceiling is required for gravity feed from the safety screen to the ball mill. This will be a prefabricated metal building with heating, ventilation, air conditioning, insulation, and lighting.

Cost: Unit Cost
Foundation $4.50/sq ft
Shell 8.50/sq ft for 12 ft
add $0.25/ft over 12 ft
8.50 + (30-12)x.25 = 13.00/sq ft
3-in. wall insulation 0.48/sq ft
4-in. ceiling insulation 0.55/sq ft
Electrical 5.59/sq ft
Door $475/ea

Total Unit Cost per sq ft (floor) = $23.69

Total Cost

30ft x 40ft x $23.69/sq ft +
2 x 30ft x 30ft + 2 x 30ft x 40ft) x $0.55 +
2 x $475 = $31,688

Subtotal	$1,398,351
Contingency and Engineering (20 percent)	$ 279,670
Total Capital Cost	$1,678,021

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